NASA DoD -55°C to +125°C Thermal Cycle Test Results

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ABSTRACT
Lead-free soldering processes and materials has been completely implemented in the commercial electronics sector due to the European Union Waste Electrical and Electronic Equipment (WEEE) and Reduction of Hazardous Waste (RoHS) Directives. These environmental legislative directives were targeted at industrial and commercial electronic products but had an unintended impact on aerospace/defense products due to global supply chain transition actions. A group of industry, academia, and government agencies initiated a lead-free solder alloy reliability investigation, building on a previous activity, to characterize and understand various aspects of lead-free solder joint integrity under -55°C to +125°C thermal cycle conditions. The goal of the testing was to generate reliability data for test vehicles that were representative of IPC Class III High Performance Electronic products.

Key words: lead-free, reliability, thermal cycle testing, aerospace

BACKGROUND
The NASA-DoD Lead-Free Electronics Project is a continuation of the Joint Council on Aging Aircraft/Joint Group on Pollution Prevention (JCAA/JGPP) Lead-Free Solder Project [1]. This project included an investigation of a series of lead-free solder alloys using the requirements of the aerospace and military community, with a focus on the rework of SnPb and lead-free solder alloys and the mixing of SnPb and lead-free solder alloys (i.e. mixed metallurgy solder joints) on a printed wiring assembly.

The JCAA/JGPP investigation selected the following solder alloys for testing:

- **Sn3.9Ag0.6Cu** (SAC) for reflow and wave soldering (SAC396: Tin (Sn); Silver (Ag); Copper (Cu))
- **Sn3.4Ag1.0Cu3.3Bi** (SACB) for reflow soldering (SACB: Tin (Sn); Silver (Ag); Copper (Cu); Bismuth (Bi))
- **Sn0.7Cu0.05Ni** (SN100C) for wave soldering (SN100C:Tin (Sn); Copper (Cu); Nickel (Ni); Germanium (Ge))
- **Sn37Pb** (SnPb) for reflow and wave soldering

The NASA DoD Lead-free investigation selected these solder alloys for testing:

- **Sn3.0Ag0.5Cu** for reflow and manual soldering (SAC305: Tin (Sn); Silver (Ag); Copper (Cu))
- **Sn0.7Cu0.05Ni** for reflow, wave, and manual soldering (SN100C:Tin (Sn); Copper (Cu); Nickel (Ni); Germanium (Ge))
- **Sn37Pb** (SnPb) for reflow, wave, and manual soldering

The NASA DoD Lead-free investigation revised the solder alloys selected for this round of testing due to the pervasive industry use of SAC305 alloy and the emerging interest of the electronics industry in Tin/Copper–modified solder alloy compositions such as the SN100C alloy. The Sn37Pb solder alloy was again included for a baseline comparison.

The majority of NASA DoD test tasks were identical to those completed for the JCAA/JGPP LFS Project. However, several additional investigation variables were included to address questions identified from the initial investigation results:

1. Determine the reliability of reworked solder joints in high-reliability military and aerospace electronics assemblies including mixed metallurgy situations.
2. Assess the process parameters for reworking high-reliability lead-free military and aerospace electronics assemblies.
3. Assess the reliability of chip scale packages (CSPs) and quad flat pack no-lead packages (QFNs)
4. Characterize the solder joint reliability of the test vehicles under Drop Shock test conditions

OBJECTIVE
The objective of the study was to compare the solder joint integrity of selected lead-free solder alloys to Sn63/Pb37 solder alloy for a -55°C to +125°C temperature range in accordance with the IPC-9701 specification under various as-manufactured and reworked conditions.

PROCEDURES

Test vehicle

Figure 1 illustrates the test vehicle used in thermal cycle testing. The circuit board was 14.5 inches wide by 9 inches high by 0.090 inches thick and contained 6 layers of 0.5 ounce copper. The test vehicle was designed to meet IPC-6012, Class 3, Type 3 requirements. The laminate was FR4 per IPC-4101/26 with a minimum Tg of 170ºC and the majority of the test vehicles used an immersion silver surface finish. A small subset of test vehicles was procured with an electroless nickel / immersion gold (ENIG) surface finish. This laminate is the same material used in the JCAA/JGPP test vehicle thus enabling "apples-to-apples" data comparisons. In total, 193 test vehicles were produced using the same printed wiring board fabricator that manufactured the JCAA/JGPP test vehicle.

Figure 1 Test Vehicle Design

All test vehicles were categorized as "Manufactured" or "Reworked". "Manufactured" test vehicles represent printed wiring assemblies newly manufactured for use in new product. "Rework" test vehicles represent printed wiring assemblies on which some components were reworked prior to environmental testing. Mixed metallurgy situations were created to establish the following test scenarios:

1. Forward Compatibility: a SnPb component is attached to a printed wiring assembly using lead-free solder with a lead-free profile.
2. Backward compatibility: a lead-free is component attached to a printed wiring assembly using SnPb solder with a SnPb solder profile.

In addition to the NASA-DoD Lead-Free Electronics Project test vehicles, the Naval Surface Warfare Center Crane Division (a NASA-DoD Consortium member), added 30 test vehicles to the NASA-DoD project in support of the Naval Supply Command (NAVSUP) sponsored "Logistics Impact of Lead-Free Circuits/Components" project. The primary purpose of the 30 test vehicle add-on was to perform multiple pass SnPb rework, once or twice, on randomly selected lead-free DIP, TQFP-144, TSOP-50, LCC and QFN components from SAC305 and SN100C soldered assemblies. Five of these test assemblies were included in the -55°C to +125°C thermal cycle testing to allow for data comparison purposes.

Test Components

A variety of component types and component finishes were included on the test vehicle. The test vehicle design incorporates components that are representative of the parts used in military/aerospace systems and is designed to reveal relative differences in solder alloy performance. The ceramic leadless chip carrier (CLCC) and thin small outline package (TSOP) component types were selected due to industry acknowledged solder joint integrity issues in Class III High Performance electronic products. The dual in-line package (DIP) components were selected to provide an example of plated thru hole technology. The thin quad flat packages (TQFPs), ball grid arrays (BGAs), chip scale packages (CSPs) and quad flat pack no leads (QFNs) were selected to represent surface mount technology. Table 1 lists the various component types, their associated surface finishes and procurement component number. All components were "dummy" devices with internally daisy-chained pins and contained simulated die. All components were procured from two sources: Practical Components and Texas Instruments.

CLCC-20	SAC305	20LCC-1.27mm-8.9mm-DC
	SnPb	
QFN-20	Sn	A-MLF20-.5mm-.65mm-DC
	SnPb	
QFP-144	Sn	A-TQFP144-20mm-.5mm-2.0-DC
	SnPb	
	NiPdAu	
	SAC305	
PBGA-225	SnPb	PBGA225-1.5mm-27mm-DC
	SAC405	
PDIP-20	Sn	A-PDIP20T-7.6mm-DC
	NiPdAu	
CSP-100	SnPb	A-CABGA100-.8mm-1.0mm-DC
	SAC105	
	SN100C	
TSOP-50	Sn	A-TII-TSOP50-10.16x20.95mm-.8mm-DC
	SnBi	
	SnPb	

Table 1 Component types and finishes

Destructive Physical Analysis (DPA) was performed on samples from each of the component types used on the test vehicles. This was done to ensure that the components used in testing met the consortia required standards and to provide component specific dimensions/properties for use by the modeling community.

Test Vehicle Assembly

The test vehicles were assembled at the BAE Systems Irving, Texas facility. A detailed description of the specific tin/lead and lead-free soldering processes was detailed in the NASA-DoD Lead-Free Electronics Project Plan [2]. Table 2 lists the various categories of test vehicles that were assembled for the consortia testing plan.

Batch	Test Vehicle Type	Reflow Solder	Wave Solder
A	Lead-Free Rework All Test Vehicles	SAC305	SN100C
B	SnPb Rework* All Test Vehicles	SnPb*	SnPb*
C	SnPb Manufactured Test Vehicles Thermal Cycle and Combined Environments	SnPb	SnPb
D	SnPb Manufactured Test Vehicles Vibration, Mechanical Shock and Drop	SnPb	SnPb
E	Lead-Free Manufactured Test Vehicles Thermal Cycle and Combined Environments	SAC305	SN100C
F	Lead-Free Manufactured Test Vehicles Vibration, Mechanical Shock and Drop	SAC305	SN100C
G	Lead-Free Manufactured Test Vehicles Thermal Cycle and Combined Environments	SN100C	SN100C
H	Lead-Free Manufactured Test Vehicles Vibration, Mechanical Shock and Drop	SN100C	SN100C
I	Lead-Free Manufactured Test Vehicles Crane Rework Effort	SN100C	SN100C
* NOTE: Lead-Free profiles will be used for reflow and wave soldering			

Table 2 Test Vehicle Assembly Details

* Table note: lead-free profiles were used for reflow and wave soldering due to component finish configuration
All test vehicles were X-rayed and visually inspected in accordance with the IPC-JSTD-001 specifications for solder joint quality.

Test Vehicle Rework

One of the primary investigation variables was the rework of specific component types. Multiple facilities performed the rework activities – BAE Systems in Irving, Texas, Lockheed Martin in Ocala, Florida, and Rockwell Collins in Cedar Rapids, Iowa – in accordance with a very detailed, regimented consortia defined protocol. The rework protocol was based on IPC rework/repair specifications with some tailoring due to the consortia test vehicle component locations. Reworked components were grouped by rework solder alloy / material (i.e. SnPb, Flux only, SAC305 and SN100C). Each facility performing the rework decided their order to rework the solder alloy / material groups, but was required to use the detailed procedure for specific component locations within the solder alloy / material group. When reworking a component, the component was removed and replaced before moving to the next component. All details regarding the rework procedure, including temperature profiles, are contained in the NASA-DoD Lead-Free Electronics Project Plan [2].

TESTING PARAMETERS AND METHODOLOGY

THERMAL CYCLE PARAMETERS AND METHODOLOGY

The temperature cycle range used for the testing was -55ºC to +125ºC with a 30 minute dwell at the high temperature extreme and a 10 minute dwell at the low temperature extreme. A maximum temperature ramp of 10°C/minute was used in the testing. The continuity of the components was continuously monitored throughout thermal cycle testing by an event detector in accordance with the IPC-9701 specification, with each component treated as a single resistance channel. An 'event' was recorded if the resistance of a channel exceeded 300 Ω for more than 0.2 μsec. A failure was defined when a component either:

- Recorded an event for 15 consecutive cycles,
- Had five consecutive detection events within 10% of current life of test, or
- Became electrically open.

Once a solder joint was designated a failure, the event detection system software excluded it from the remainder of the test. Detailed temperature profiling was conducted prior to the beginning of the thermal cycle conditioning to ensure that each test vehicle was subjected to uniform, consistent exposure to the test chamber temperatures. In the Rockwell Collins consortia thermal cycle testing effort, a total of 8 Manufactured, 19 Reworked and 8 Crane test vehicles were placed in the chamber (the total component population of 2,240). Figure 2 (Left) illustrates the thermal cycle temperature profile for the -55ºC to +125ºC testing and the resulting measured test vehicle temperatures. Figure 3 (Right) illustrates the test vehicles positioned in the -55ºC to +125ºC test chamber.

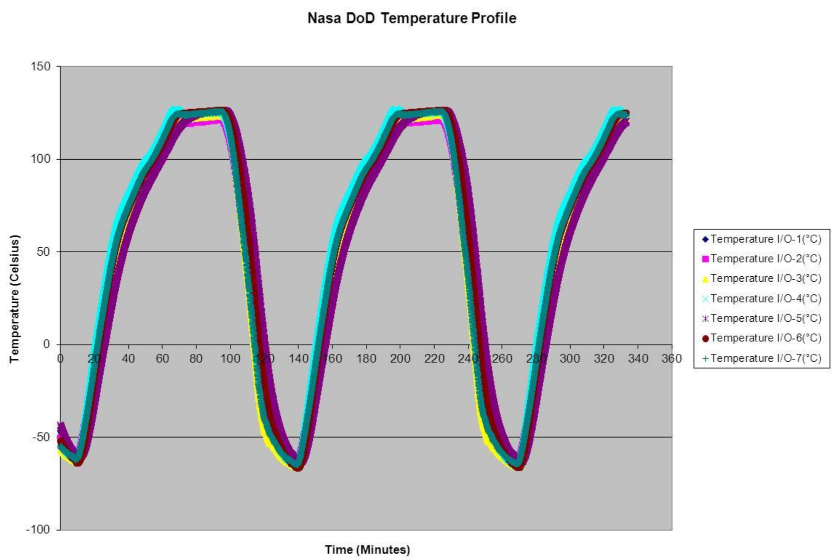


Figure 2: Thermal cycle profile for the -55ºC to +125ºC Conditioning

Figure 3: Test Vehicles in the Thermal Cycle Chamber

TEST RESULTS

The -55ºC to +125ºC thermal cycle testing was terminated after 4068 total thermal cycles. At that point, all of the components had reached an N63 statistical value (except for the QFN-20 component style) thus allowing for a complete statistical analysis of the compiled failure data. The Manufactured test vehicle failure rates are shown in Table 3 and Reworked test vehicle failure rates are shown in Table 4. NWSC Crane reworked the CLCCs, QFNs, TQFPs and PDIP component types with the test results statistical analysis being conducted by Rockwell Collins. The Table 4 failure rates include only the four components reworked as part of the NASA DoD portion of the investigation.

Component Type	Total Failures	Population	Percent Failed
CLCC-20	280	305	92%
QFN-20	6	135	4%
QFP-144	274	287	95%
PBGA-225	236	283	83%
PDIP-20	82	218	38%
CSP-100	163	241	68%
TSOP-50	236	238	99%

Table 3 Manufactured Test Vehicle Component Population Failure Rates after 4068 Thermal Cycles

Component Type	Total Failures	Population	Percent Failed
PBGA-225	48	66	73%
PDIP-20	36	64	56%
CSP-100	25	64	37%
TSOP-50	99	99	100%

Table 4 Reworked Test Vehicle Component Population Failure Rates after 4068 Thermal Cycles

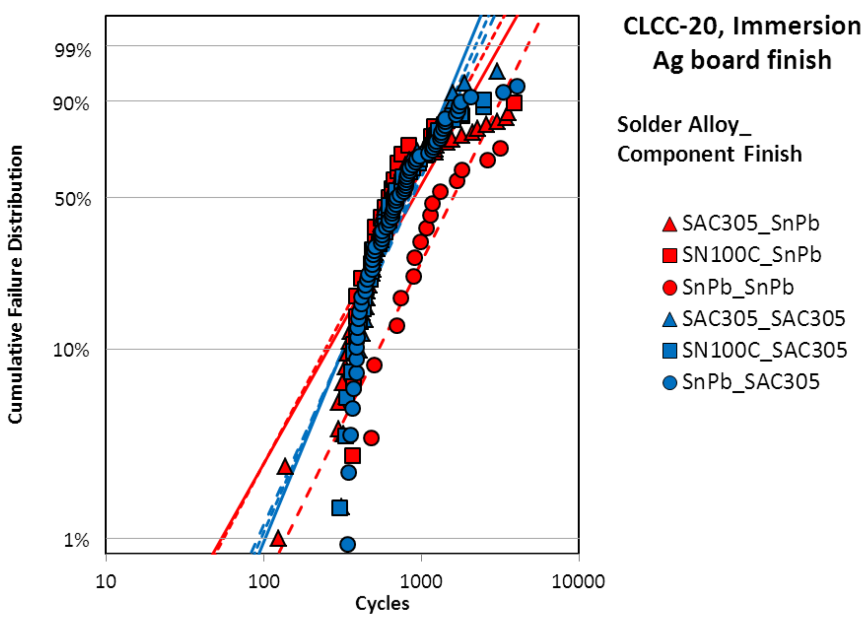
The physical failure and statistical analysis for each component type was completed with the following sections summarizing the results for each specific component style. It should be noted that the test vehicles remained in the thermal cycle chamber the entire 4068 cycles. Individual components remained in the test chamber after they had failed to avoid damaging the solder joints of other components on the test vehicles due to handling/movement. This resulted in some continuing solder joint microstructure evolution after the initial component failure, which is evident in some of the physical failure analysis pictures. The data in the following plots do not include thermal cycle results that showed a failure after 1 cycle.

Ceramic Leadless Chip Carriers (CLCC-20) Results

Statistical Analysis

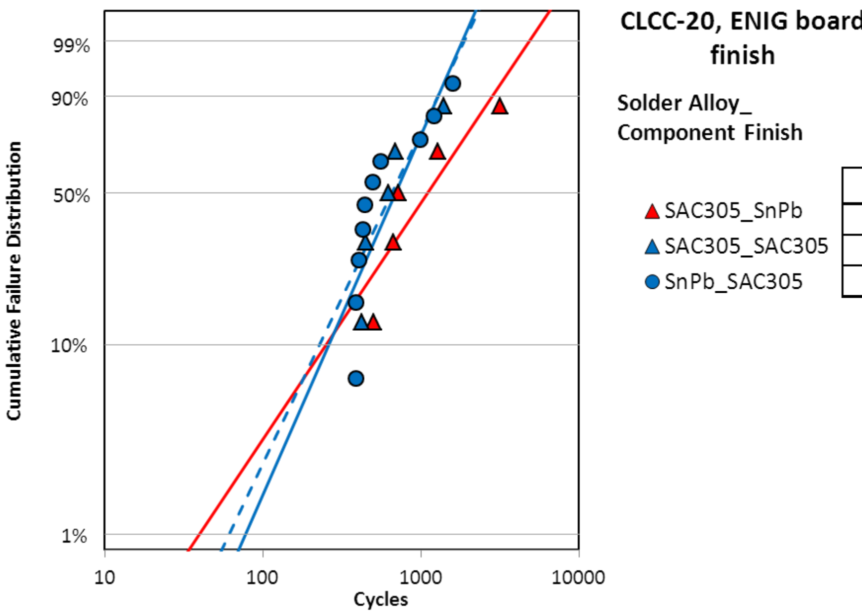
The CLCC-20 components had accumulated 92% population failure after the completion of 4068 thermal cycles. The CLCC-20 components were included on the test vehicles because of their poor reliability track record on electronic assemblies used in harsh environments. Industry data [3] has demonstrated that the CLCC component style undergoes solder joint integrity degradation under IPC Class 3 use environments due to coefficient of thermal expansion (CTE) mismatch with the printed wiring assembly. CLCC-20 components had six different combinations (SAC/SAC, SAC/SnPb, SnPb/SAC, SnPb/SnPb, SN100C/SAC, SN100C/SnPb) tested and the Weibull characteristics show N63 values ranging from 952 cycles to 1954 cycles for the immersion silver test vehicles. The SnPb/SnPb combination had best thermal cycle performance with remaining solder alloy/component finish combinations having similar performance results. The solder alloy/component surface finish combination results for the ENIG test vehicles revealed no clear favored combination as the results populations were statistically indistinguishable from each other. The CLCC-20 components reworked as part of the NSWC Crane population had no preferred thermal cycle result solder alloy/component finish combination.

The Weibull plots in Figure 4 through Figure 6 summarize the CLCC-20 thermal cycle test results.



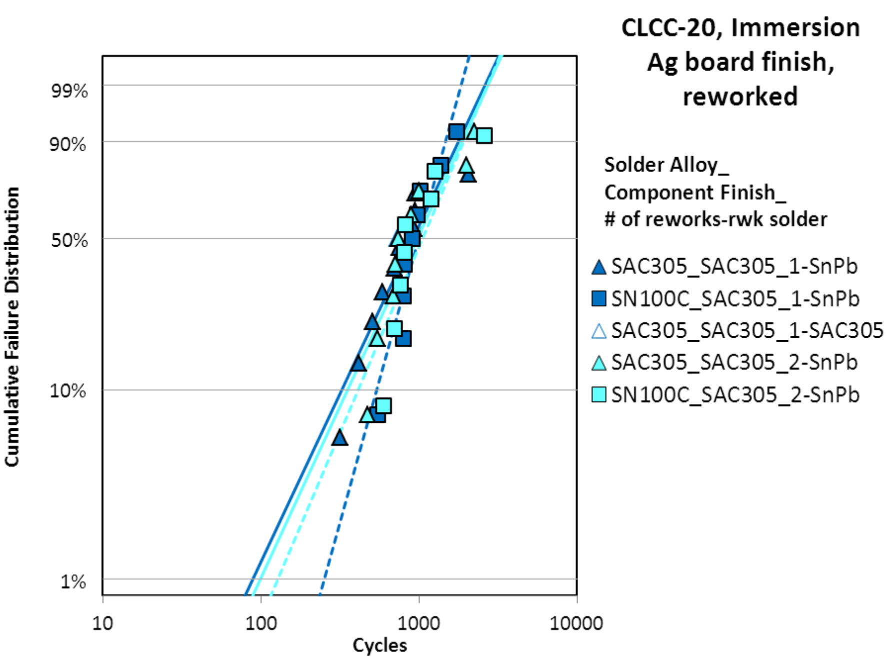
beta	N63	R^2	failed	samples
1.5	1148	79.9%	61	70
1.58	1014	63.9%	23	25
1.74	1954	85.5%	15	20
2.06	952	82.4%	46	47
1.95	1015	81.4%	44	48
1.88	1060	78.0%	71	75

Figure 4 CLCC-20 Weibull Plot for Immersion Silver Test Vehicle



beta	N63	R^2	failed	samples
1.27	1468	80.7%	5	5
1.94	836	79.2%	5	5
1.79	805	69.5%	10	10

Figure 5 CLCC-20 Weibull Plot for ENIG Test Vehicle



beta	N63	R^2	failed	samples
1.81	1122	86.9%	10	12
3.08	1120	88.0%	9	9
n/a	n/a	n/a	1	1
1.85	1195	81.5%	9	9
2	1265	74.1%	8	8

Figure 6 NWSC Crane Reworked CLCC-20 Weibull Plot

Physical Failure Analysis

Metallographic cross-sectional analysis was conducted on the CLCC-20 components to document the solder joint failure location, crack morphology and solder joint microstructure. General physical failure observations of the failed CLCC-20 components were:

- The cracks in the solder joints initiated under the components and traversed at a 45° angle thru the solder fillets. The crack formation and location are in agreement with industry published data of CLCC failure modes [4] [5].
- The solder joint geometries and wetting angles were acceptable and met industry workmanship criteria.
- The solder joint microstructures were reasonably homogenous with no segregation regions observed in the mixed metallurgy cases.

Figure 7 through Figure 11 illustrate the typical CLCC-20 solder joint failures.

Figure 7: CLCC-20 Component on Test Vehicle after 4068 Thermal Cycles

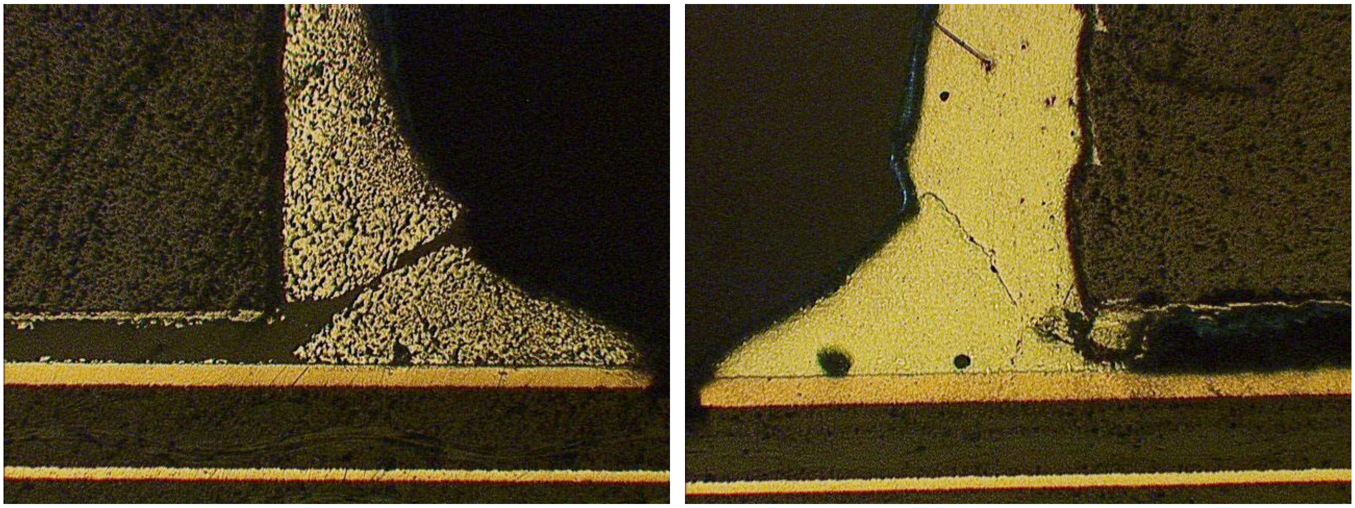


Figure 8: CLCC-20 Solder Joints, Left - Board 5, Component U14, SnPb/SnPb, Failed @ 2625 Cycles; Right - Board 43, Component U14, SAC305/SAC305, Failed @ 513 Cycles

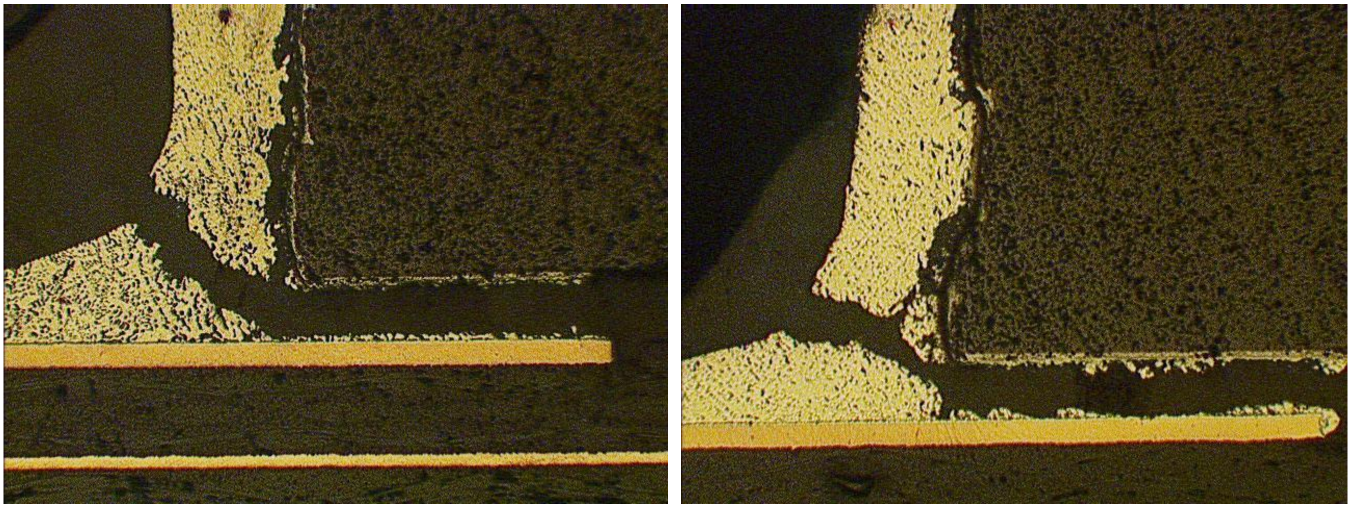


Figure 9: CLCC-20 Solder Joints, Left- Board 164, Component U14, SAC305/SnPb, Failed @ 1248 Cycles, Right - Board 126, Component U14, SnPb/SAC305, Failed @ 2064 Cycles

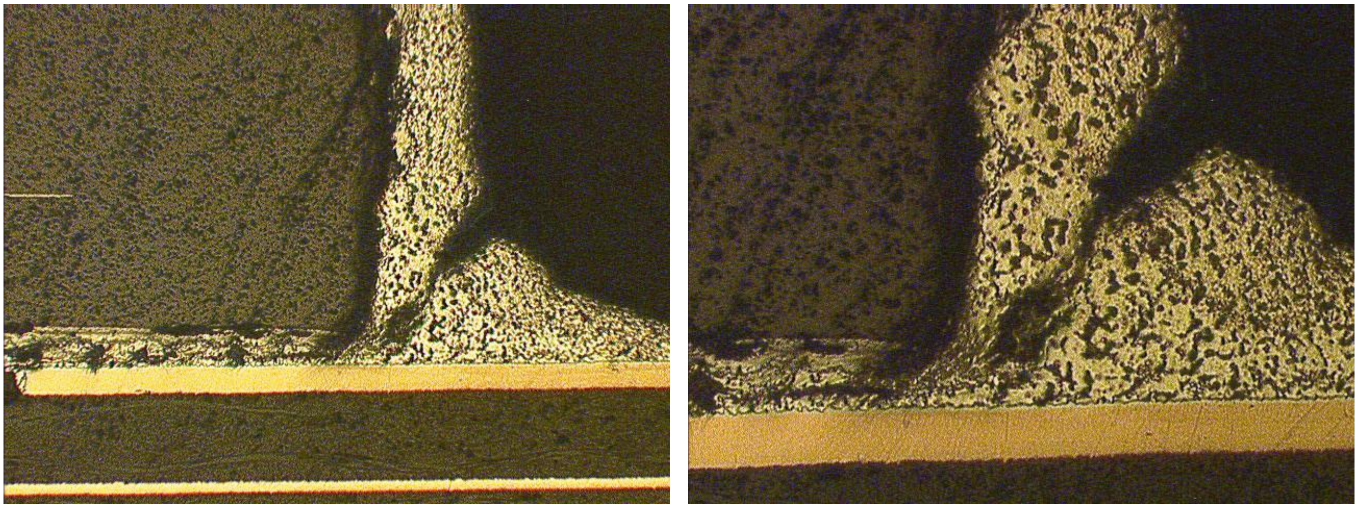


Figure 10: CLCC-20 Solder Joints, Board 103, Component U22, SN100C/SnPb, Failed @ 828 Cycles

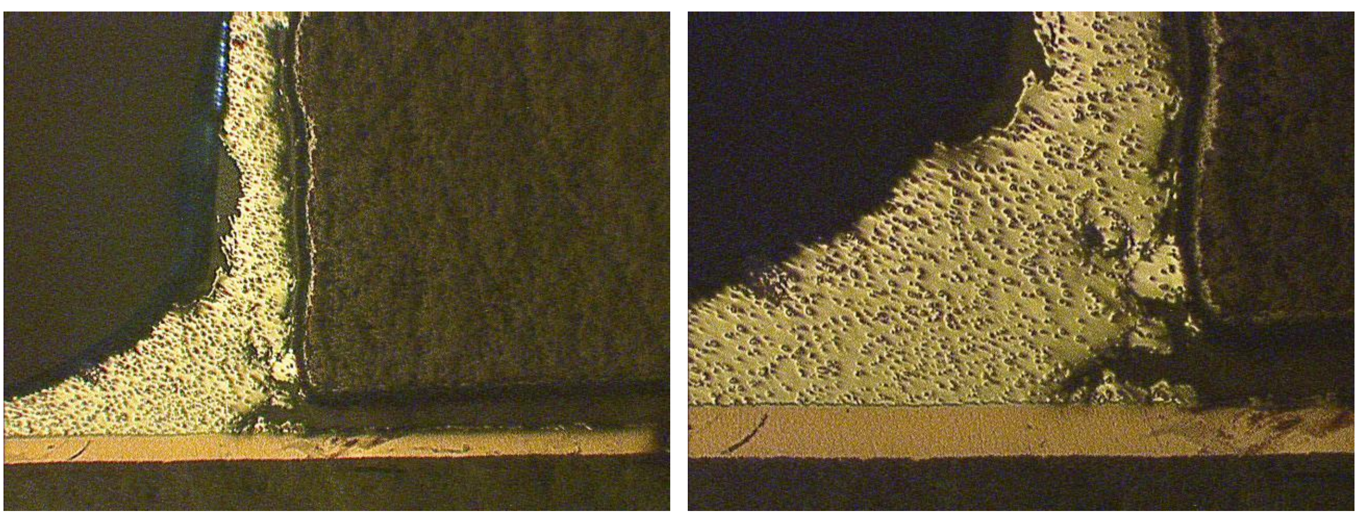


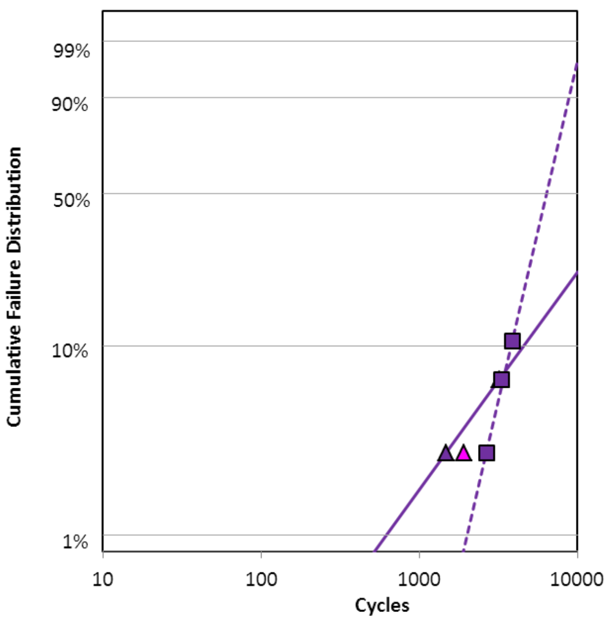
Figure 11: CLCC-20 Solder Joints, Board 104, Component U14, SN100C/SAC305, Failed @ 304 Cycles

Quad Flatpack No-Lead (QFN-20) Results

<u>Statistical Analysis</u>

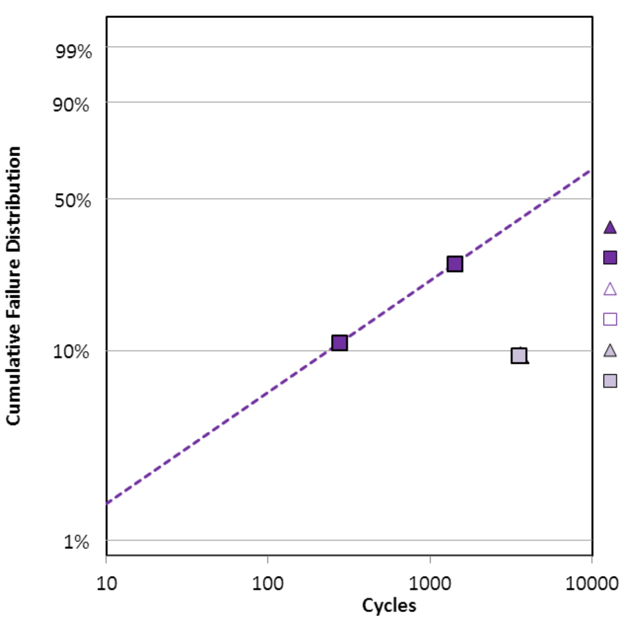
The QFN-20 components had accumulated 4% population failure after the completion of 4068 thermal cycles and were the most robust component type in the investigation. QFN-20 components had three different combinations (SAC/Sn, SN100C/Sn, SnPb/Sn) tested. Calculation of Weibull statistics was only possible for the SN100C/Sn alloy/component finish combination due to the low number of solder joint failures. The robustness of the QFN component style was demonstrated as none of the solder alloy/component finish combinations accumulated any significant number of failures. R. Coyle et al published results showing for a QFN-48 package that SnPb solder alloy performed better than a SAC405 solder alloy in 0°C -100°C thermal cycle test conditions [6]. The investigation QFN-20 data had insufficient failures to allow for a results comparison with the Coyle investigation. No alloy/component finish preferred combination conclusions could be made due to the lack of solder joint failures for the NWSC Crane reworked QFN-20 components

The Weibull plots in Figure 12 and in Figure 13 summarize the QFN-20 thermal cycle test results.



Board Finish, Solder Alloy_ Component Finish	beta	N63	R^2	failed	samples
ImAg, SAC305_Matte Sn	n/a	n/a	n/a	2	25
ImAg, SN100C_Matte Sn	3.68	7016	99.4%	3	25
ImAg, SnPb_Matte Sn	n/a	n/a	n/a	0	50
ENIG, SAC305_SnPb	n/a	n/a	n/a	1	25
ENIG, SAC305_Matte Sn	n/a	n/a	n/a	0	5
ENIG, SnPb_Matte Sn	n/a	n/a	n/a	0	5

Figure 12 QFN-20 Weibull Plot for Immersion Silver and ENIG PWB Finishes



Solder Alloy_ Component Finish_# of reworks	beta	N63	R^2	failed	samples
SAC305_Matte Sn_1	n/a	n/a	n/a	0	7
SN100C_Matte Sn_1	n/a	n/a	n/a	2	6
SAC305_Matte Sn_2	n/a	n/a	n/a	0	6
SN100C_Matte Sn_2	n/a	n/a	n/a	0	7
SAC305_Matte Sn_StencilQuik	n/a	n/a	n/a	1	7
SN100C_Matte Sn_StencilQuik	n/a	n/a	n/a	1	7

Figure 13 NWSC Crane Reworked QFN-20 Weibull Plot

Physical Failure Analysis

- Metallographic cross-sectional analysis was conducted on the QFN-20 components to document the solder joint failure location, crack morphology and solder joint microstructure. It should be noted that the QFN-20 components contained a metallized thermal pad that was soldered to the test vehicles that has a significant influence on the thermal cycle solder joint integrity in comparison to QFN components without metallized thermal pads. General physical failure observations of the failed QFN-20 components were:
- The cracks in the solder joints initiated in the bottom terminated pads and traversed towards the lead toe. The crack formation and location are in agreement with industry published data of QFN failure modes [6] [7].
- The solder joint geometries and wetting angles were acceptable and met industry workmanship criteria. The ground pad on the QFN-20 components achieved 50% minimum solder coverage and no cracking was observed in that solder joint.
- The solder joint microstructures were homogenous with no segregation regions observed. The solder paste alloy completely dominated the solder joint microstructure regardless of the component surface finish.
- The Stencil Quik reworked solder joints were significantly thicker than the traditionally reworked solder joints (Figure 20 and Figure 21).

Figure 14 through Figure 21 illustrate the typical QFN-20 solder joint failures.

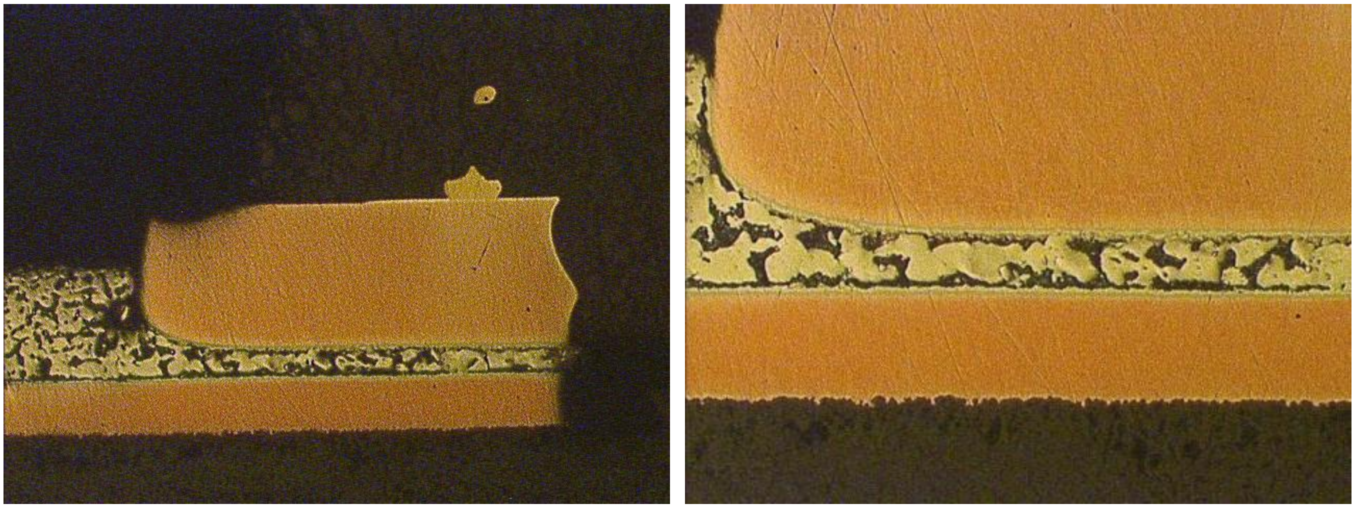


Figure 14: QFN-20 Solder Joints, Board 6, Component U27, SnPb/Sn Dipped, Did Not Fail (DNF)

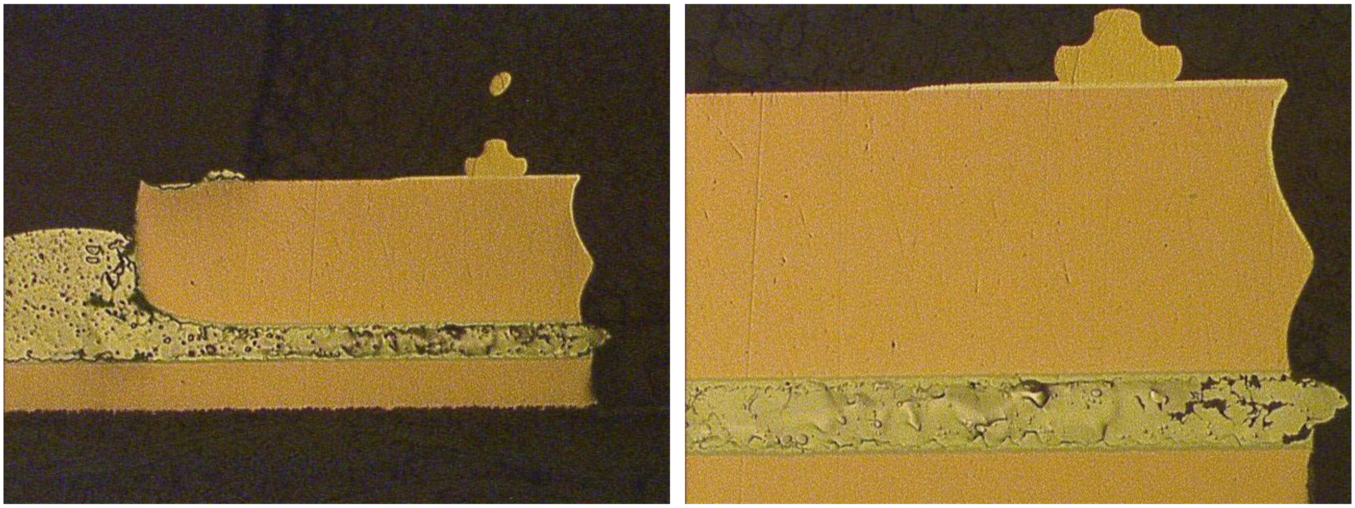


Figure 15: QFN-20 Solder Joints, Board 42, Component U54, SAC305/Sn, DNF

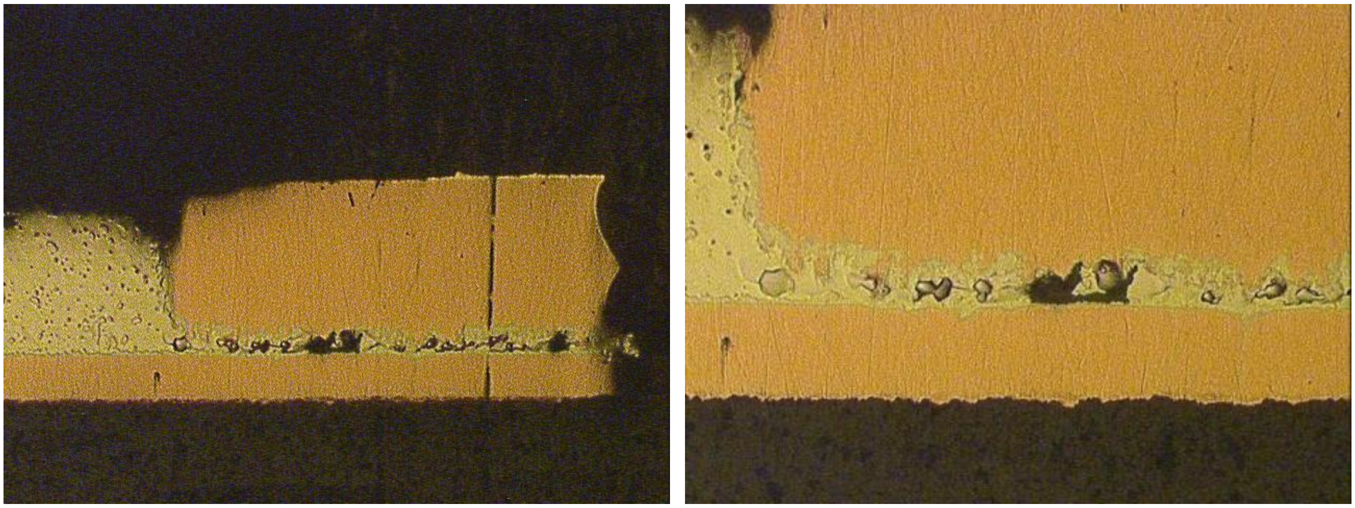


Figure 16: QFN-20 Solder Joints, Board 104, Component U27, SN100C/Sn, DNF

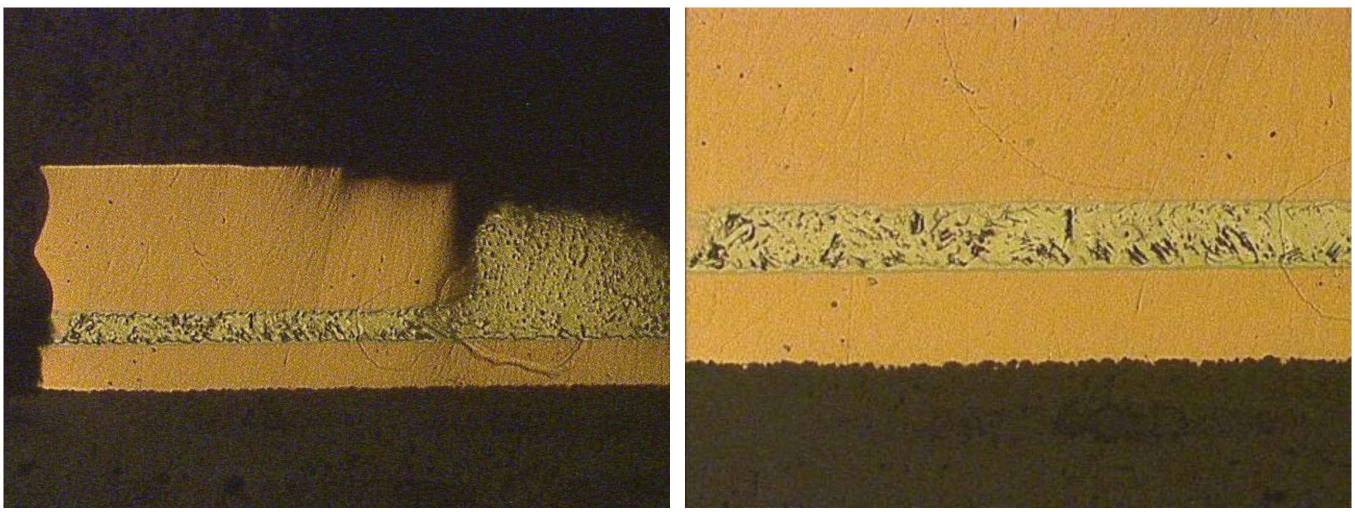


Figure 17: QFN-20 Solder Joints, Board 167, Component U15, SAC305/SnPb, DNF

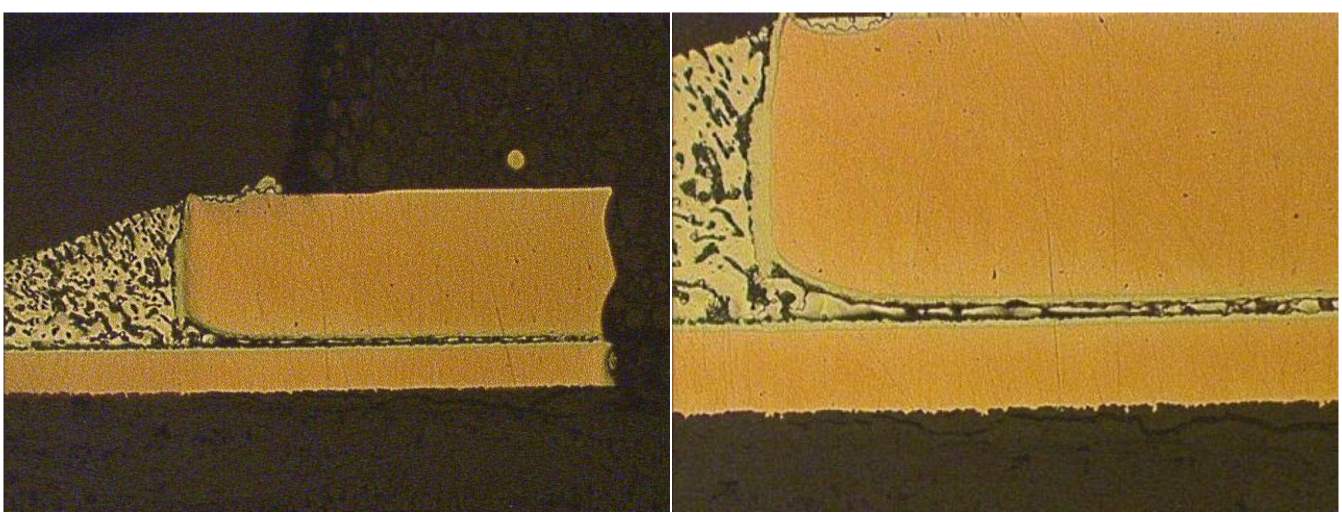


Figure 18: QFN-20 Solder Joints, Board 107, Component U28, SN100C/Sn, Reworked with SnPb Paste, 1 Rework Failed @ 277 Cycles

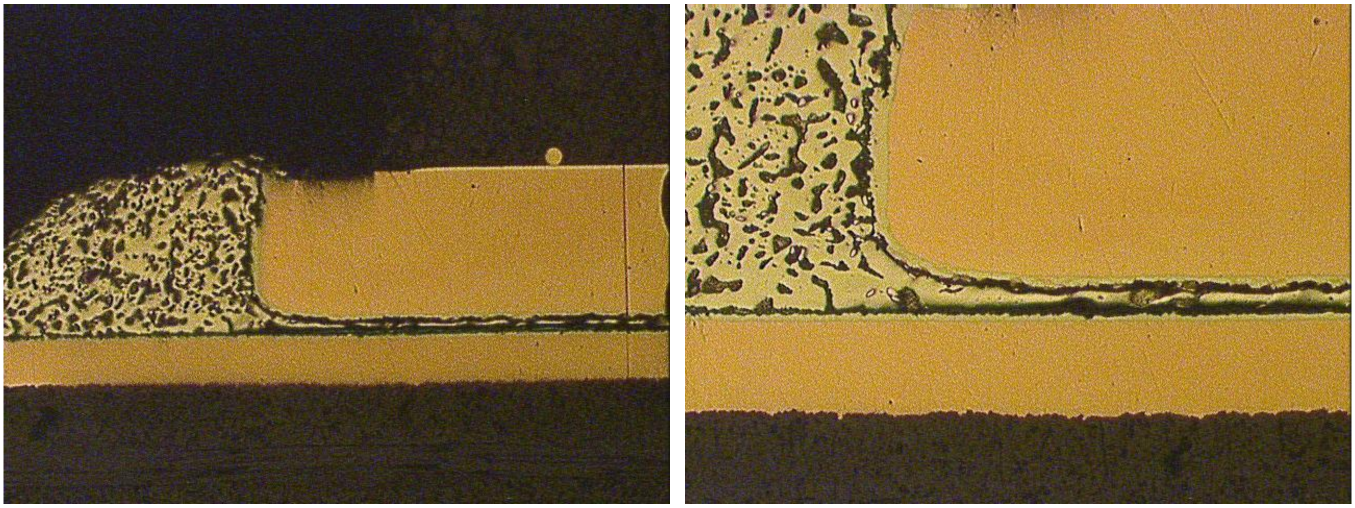


Figure 19: QFN-20 Solder Joints, Board 108, Component U28, SN100C/Sn, Reworked with SnPb Paste, 2 Reworks, DNF

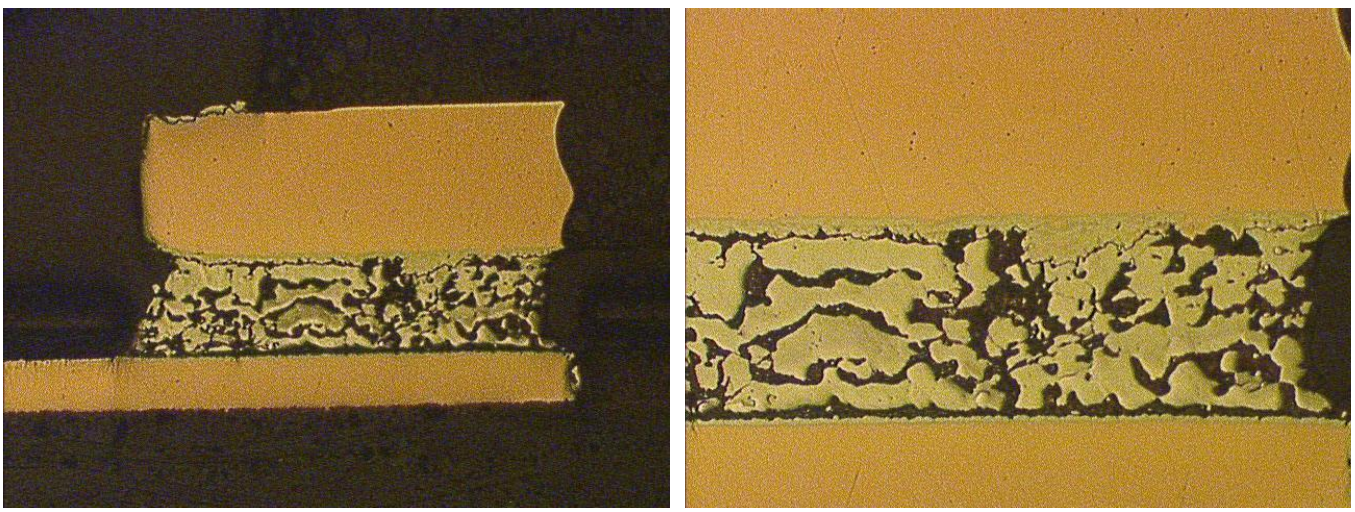


Figure 20: QFN-20 Solder Joints, Board 109, Component U28, SN100C/Sn, Reworked with Stencil Quik, 1 Rework, DNF

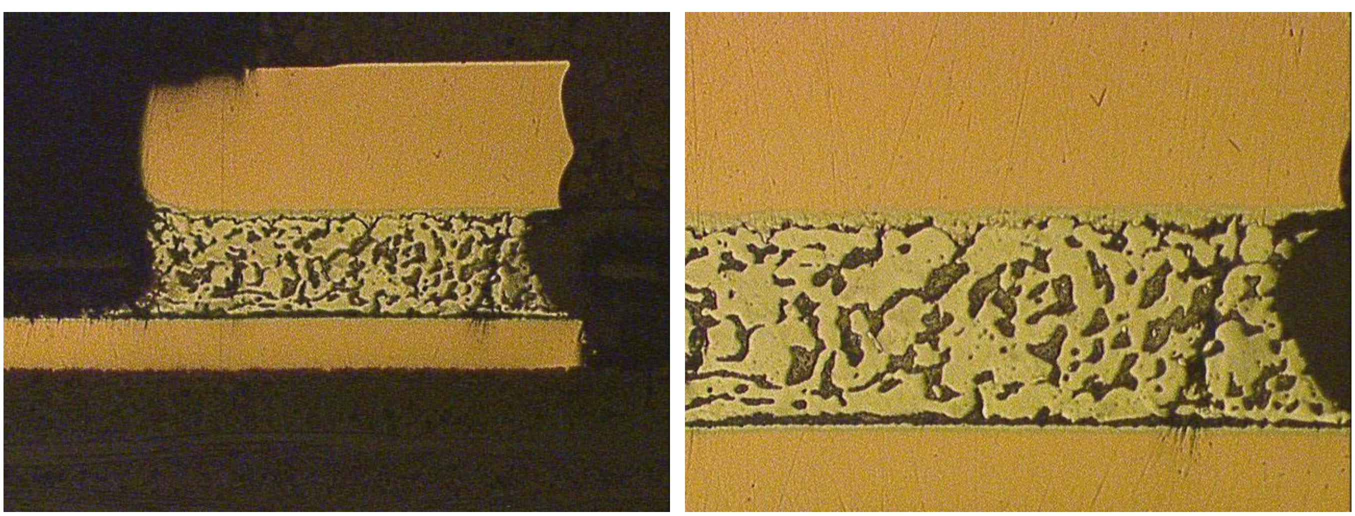


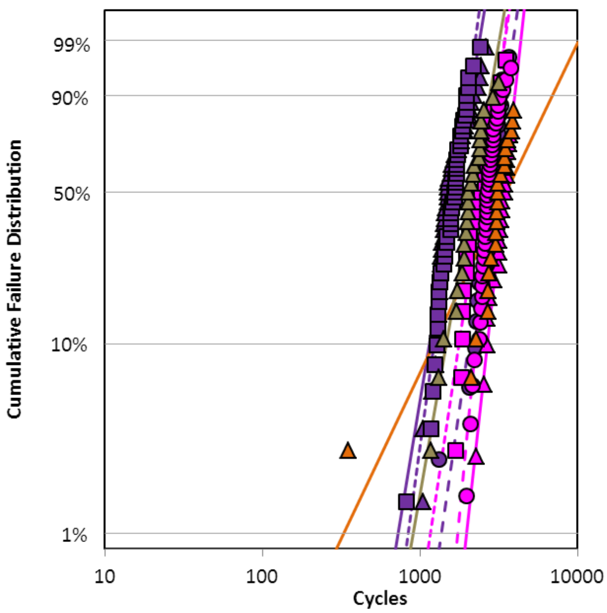
Figure 21: QFN-20 Solder Joints, Board 47, Component U15, SAC305/Sn, Reworked with Stencil Quik, 1 Rework, Failed @ 3660 Cycles

Thin Quad Flatpack Package (TQFP-144) Results

Statistical Analysis

The TQFP-144 components had accumulated 95% population failure after the completion of 4068 thermal cycles. TQFP-144 components had eight different combinations (SAC/Sn, SAC/SnPb, SAC/SAC, SnPb/NiPdAu, SnPb/SnPb, SnPb/Sn, SN100C/Sn, SN100C/SnPb) and the Weibull characteristics show very similar N63 values for the immersion silver test vehicles. None of the solder alloy/component finish combinations performed significantly better than another. This is not a surprising result as QFP components have excellent industry solder joint integrity under a variety of conditions due to the package lead compliancy. The solder alloy/component surface finish combination results for the ENIG test vehicles revealed no clear favored combination as the results populations were statistically indistinguishable from each other. The TQFP-144 components reworked as part of the NSWC Crane population had no preferred thermal cycle result solder alloy/component finish combination.

The Weibull plots in Figure 22 through Figure 23 summarize the TQFP-144 thermal cycle test results.

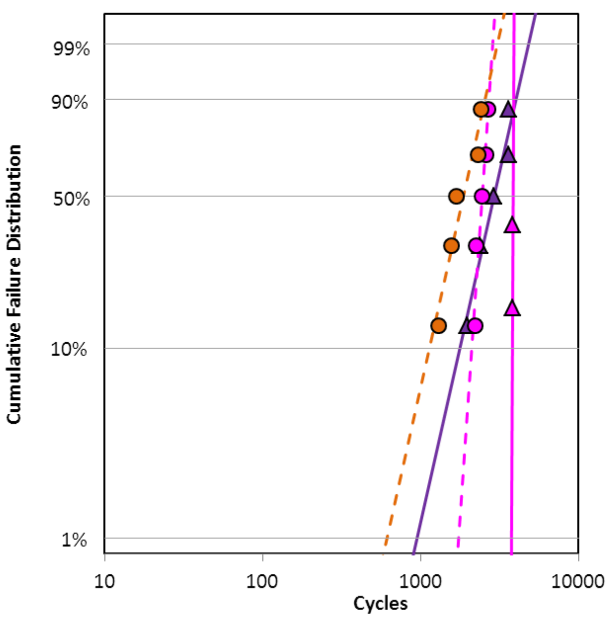


TQFP-144, Immersion Ag board

Solder Alloy_ Component Finish

Solder Alloy_Component Finish	beta	N63	R^2	failed	samples
SAC305_Matte Sn	5.15	1774	85.6%	47	47
SN100C_Matte Sn	6.25	1756	96.6%	47	47
SnPb_Matte Sn	5.85	3003	91.4%	28	28
SAC305_SnPb Dip	7.75	3582	98.0%	21	27
SN100C_SnPb Dip	5.63	2637	91.7%	25	25
SnPb_SnPb Dip	8.97	2901	92.3%	43	44
SAC305_NiPdAu	1.79	4315	64.1%	22	25
SnPb_NiPdAu	4.87	2333	96.3%	24	25

Figure 22: TQFP-144 Weibull Plot for Immersion Silver PWB Finish

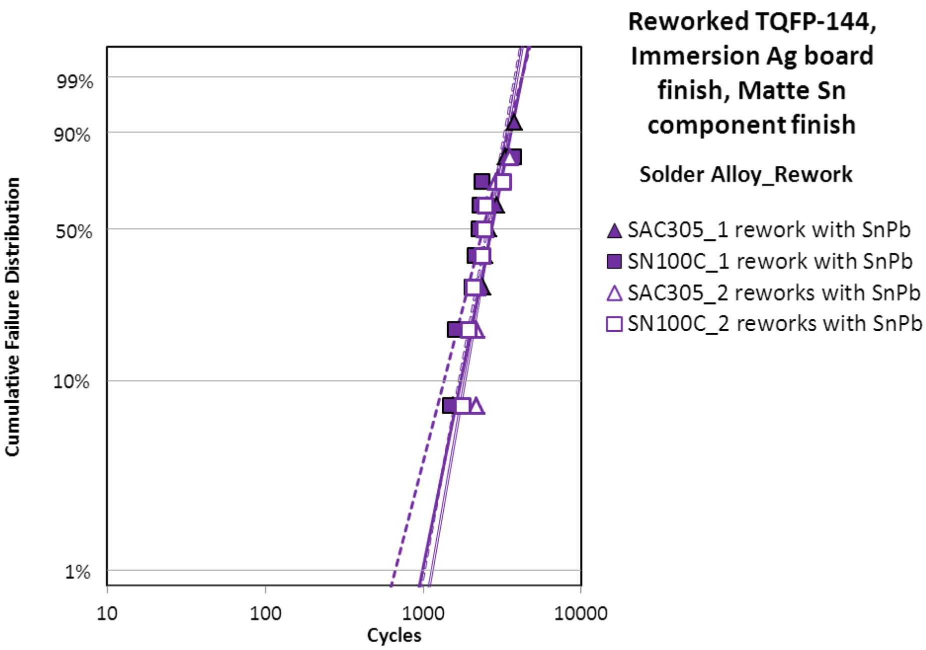


TQFP-144, ENIG board finish

Solder Alloy_ Component Finish

Solder Alloy_Component Finish	beta	N63	R^2	failed	samples
SAC305_Matte Sn	3.77	3219	94.9%	5	5
SAC305_SnPb Dip	n/a	n/a	n/a	2	4
SnPb_SnPb Dip	12.31	2531	91.0%	5	5
SnPb_NiPdAu	3.8	2057	92.9%	5	5

Figure 23: TQFP-144 Weibull Plot for ENIG PWB Finish



beta	N63	R^2	failed	samples
4.21	2943	97.8%	9	9
3.31	2664	80.9%	8	9
4.94	2882	69.0%	8	9
4.63	2742	86.7%	7	9

Figure 24: NSWC Crane Reworked TQFP-144 Weibull Plot

<u>Physical Failure Analysis</u>

Metallographic cross-sectional analysis was conducted on the TQFP-144 components to document the solder joint failure location, crack morphology and solder joint microstructure. General physical failure observations of the failed TQFP-144 components were:

- The cracks in the solder joints initiated in the heel fillet region and traversed under the foot towards the lead toe. The crack formation and location are in agreement with industry knowledge of QFP failure modes [3].
- The solder joint geometries and wetting angles were acceptable and met industry workmanship criteria. There were a number of instances where the solder did flow into the upper lead bend region which is acceptable per industry standards.
- The solder joint microstructures were reasonably homogenous with no segregation regions observed in the mixed metallurgy cases.

Figure 25 through Figure 33 illustrate the typical TQFP-144 solder joint failures observed:

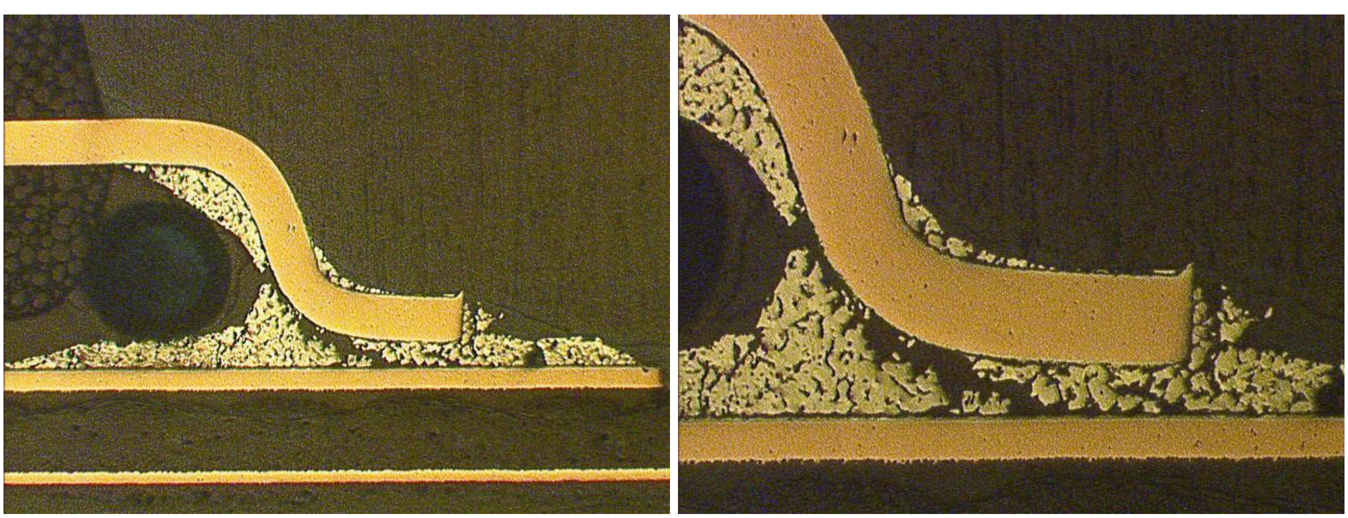


Figure 25: TQFP-144 Solder Joints, Board 9, Component U48, SnPb/SnPb Dipped, Failed @ 2648 Cycles

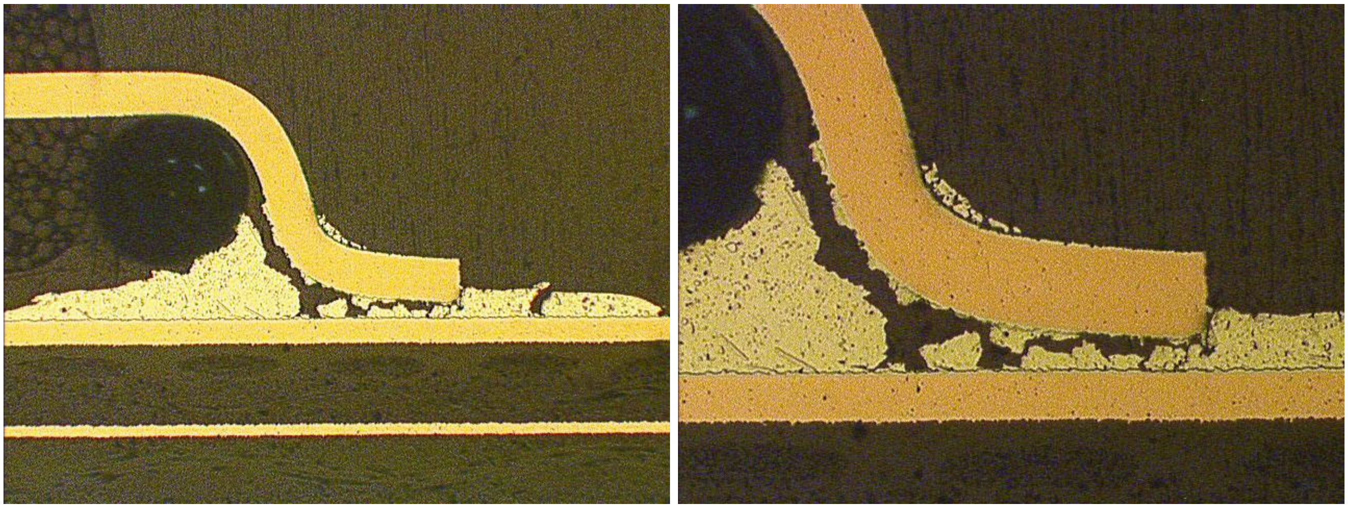


Figure 26: TQFP-144 Solder Joints, Board 41, Component U20, SAC305/SnPb Dipped, Failed @ 3541 Cycles

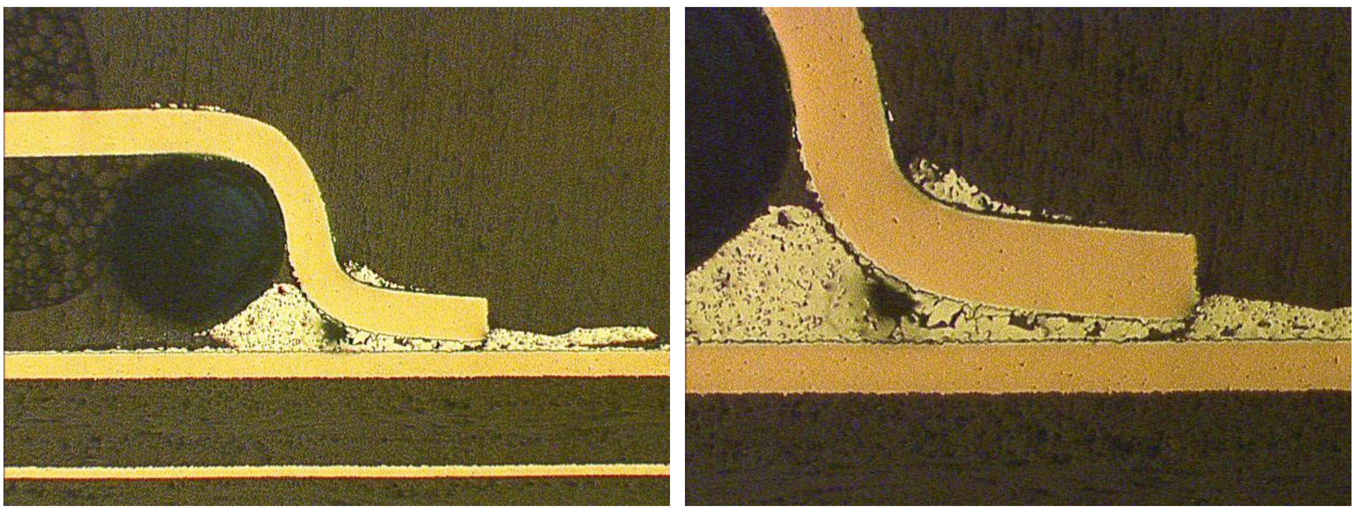


Figure 27: TQFP-144 Solder Joints, Board 106, Component U20, SN100C/SnPb Dipped, Failed @ 3258 Cycles

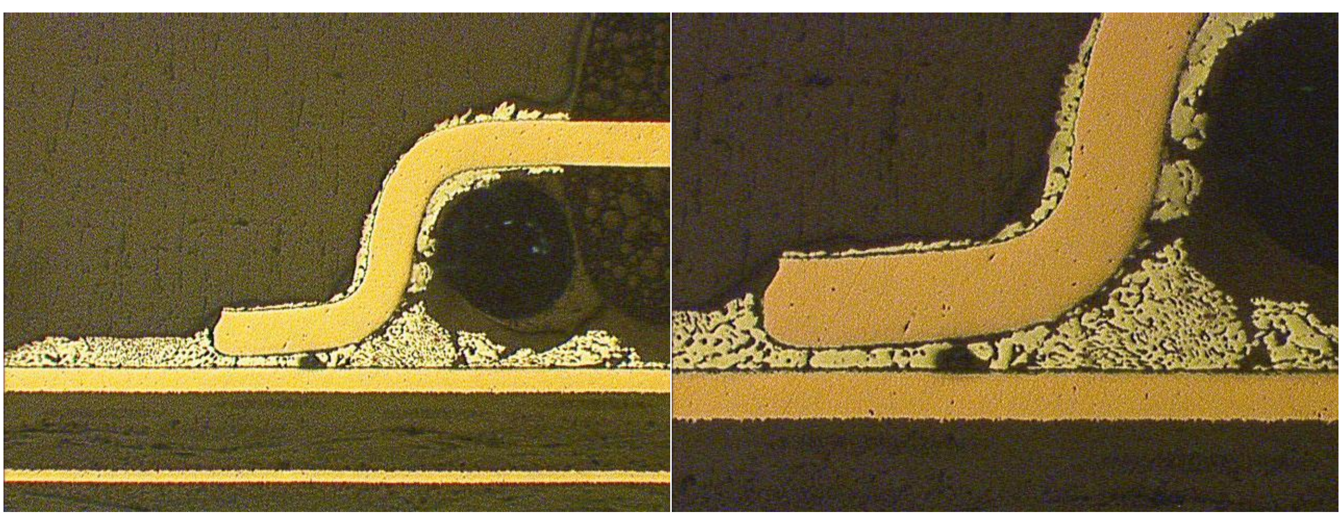


Figure 28: TQFP-144 Solder Joints, Board 9, Component U1, SnPb/Sn, Failed @ 1 Cycle

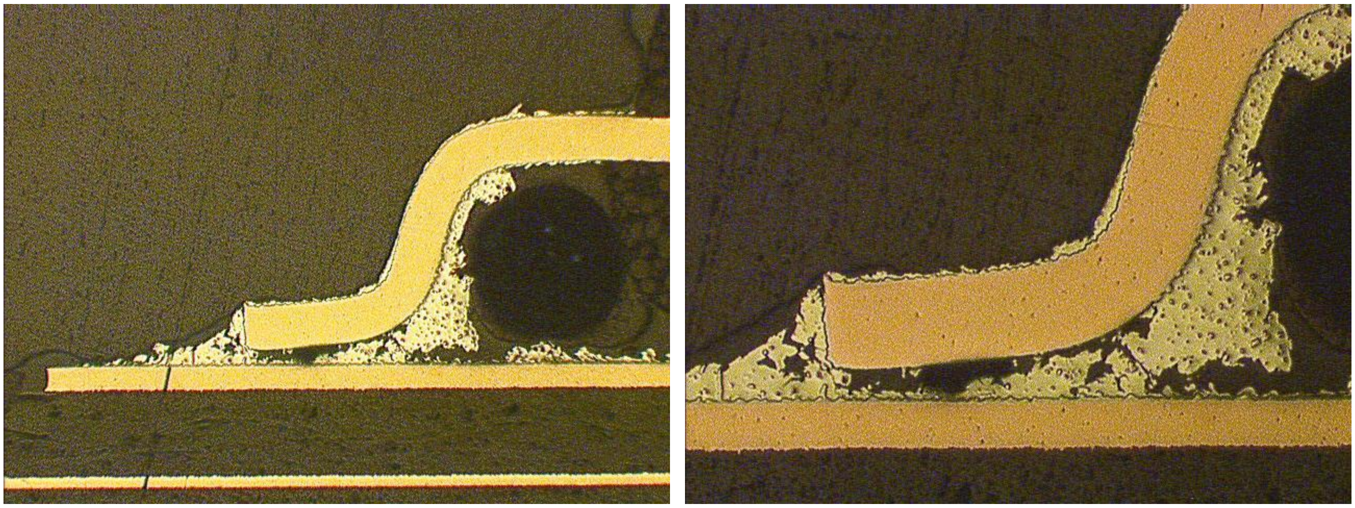


Figure 29: TQFP-144 Solder Joints, Board 49, Component U57, SAC305/Sn, Failed @ 1430 Cycles

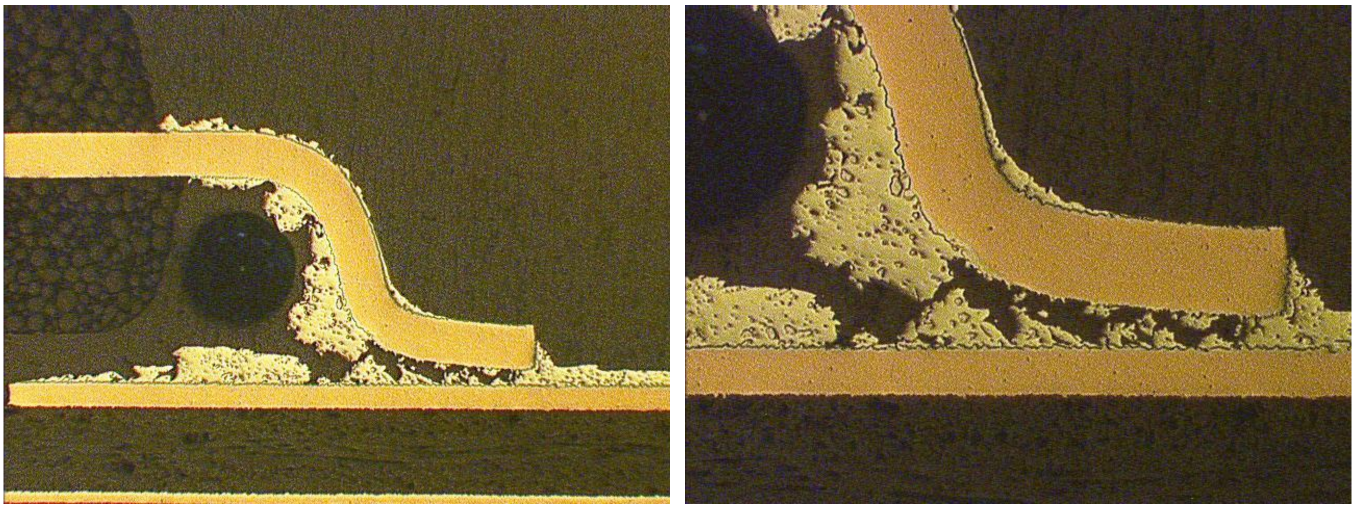


Figure 30: TQFP-144 Solder Joints, Board 103, Component U48, SN100C/Sn, Failed @ 1712 Cycles

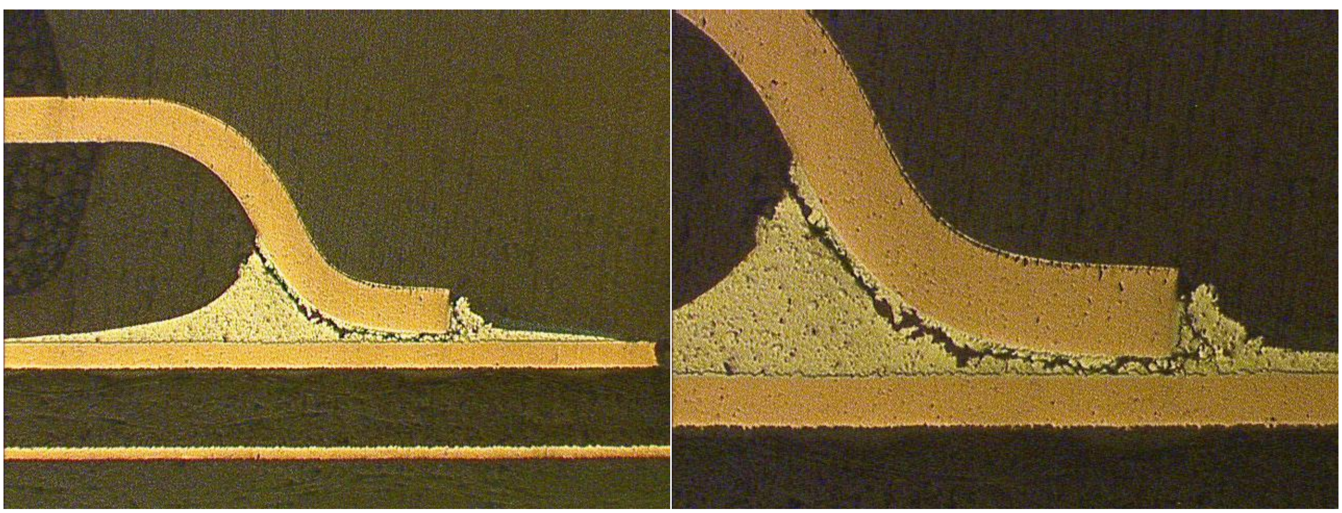


Figure 31: TQFP-144 Solder Joints, Board 167, Component U57, SAC305/NiPdAu, Failed @ 3478 Cycles

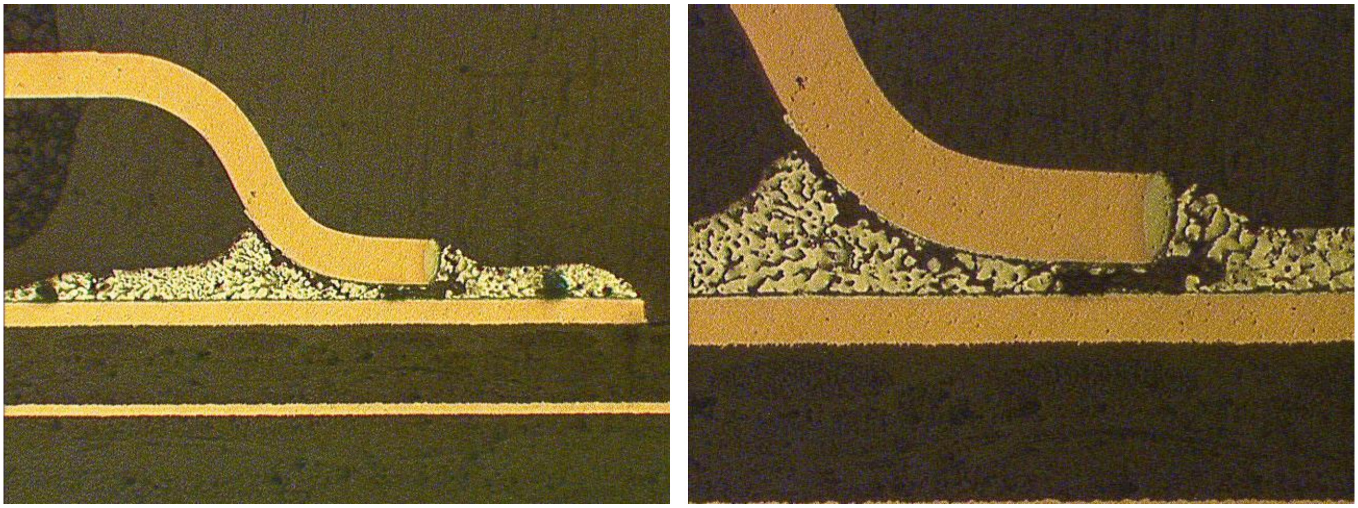


Figure 32: TQFP-144 Solder Joints, Board 127, Component U3, SnPb/NiPdAu, Failed @ 1744 Cycles

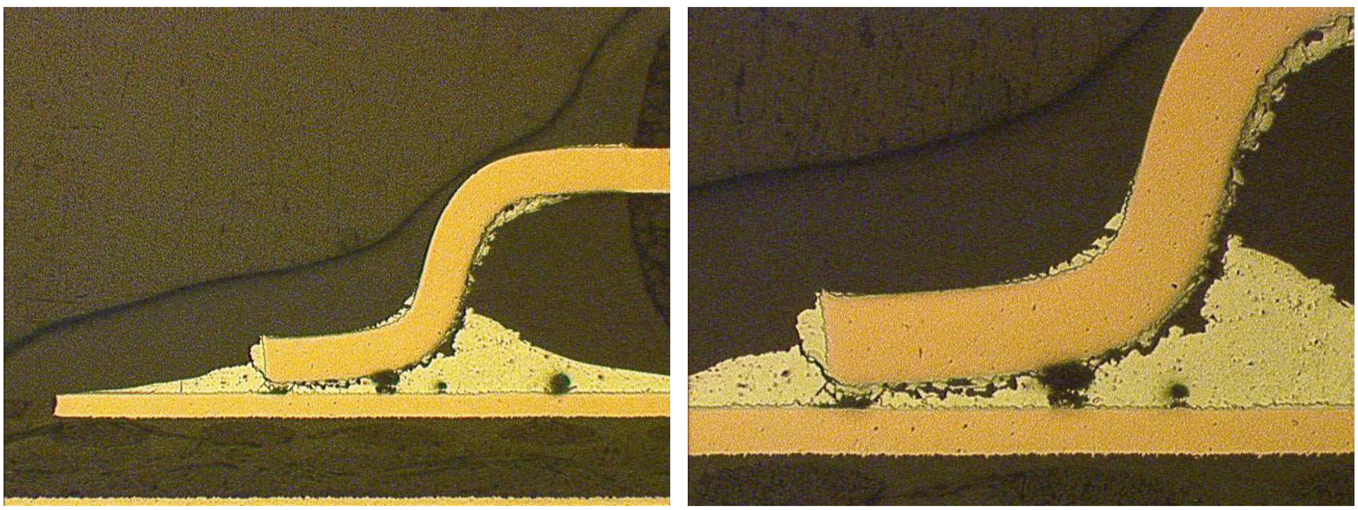


Figure 33: TQFP-144 Solder Joints, Board 164, Component U7, SAC305/SAC305, Failed @ 2359 Cycles

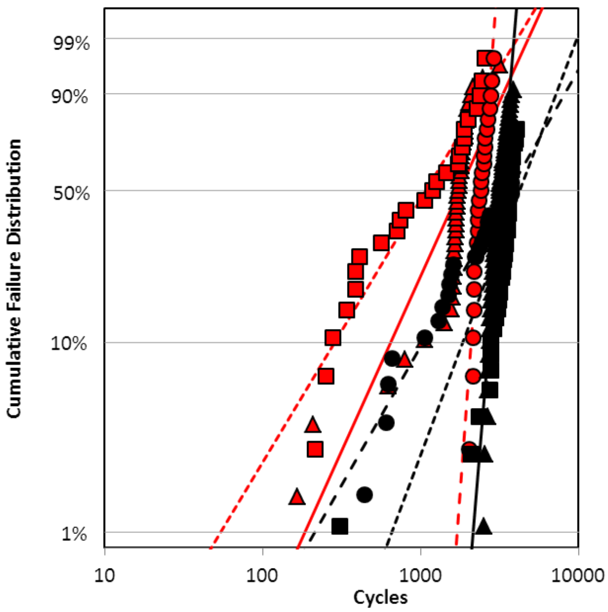
Ball Grid Array (PBGA-225) Results

Statistical Analysis

The PBGA-225 components had accumulated 83% population failure after the completion of 4068 thermal cycles. PBGA-225 components had six different combinations (SAC/SAC, SAC/SnPb, SN100C/SAC, SN100C/SnPb, SnPb/SAC, SnPb/SnPb) tested.
The non-mixed solder alloy/component finish combinations - SnPb/SnPb, SAC305/SAC405, SN100C/SAC405 - had better thermal cycle performance than the mixed metallurgy combinations. This result is in agreement with the JCAA/JGPP program PBGA thermal cycle results. The number of solder joint failures for the ENIG test vehicles was very small and therefore no conclusions were made.

The reworked PBGA-225 components had accumulated 73% population failure after the completion of 4068 thermal cycles. The same failure trend was observed for the reworked PBGA-225 as observed for the manufactured PBGA-225 components: non-mixed solder alloy/component finish combinations had better thermal cycle performance than the mixed metallurgy combinations. The number of solder joint failures for the ENIG test vehicles was very small and therefore no conclusions were made.

The Weibull plots in Figure 34 thru Figure 37 summarize the PBGA-225 thermal cycle test results.

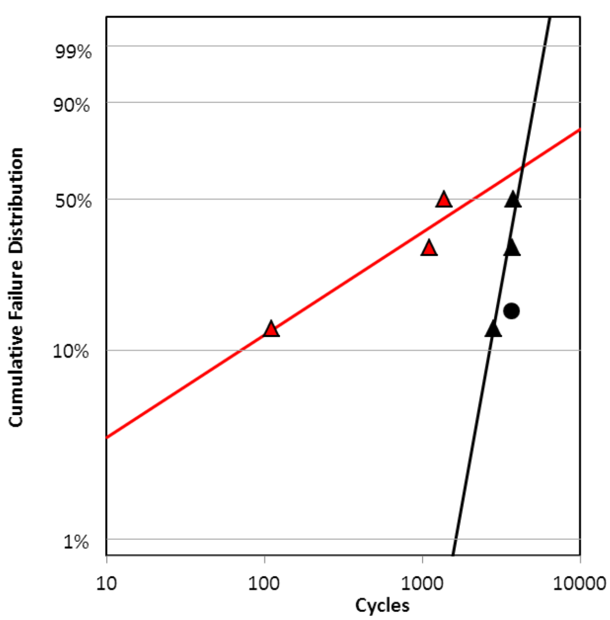


BGA-225,
Immersion Ag board

Solder Alloy_
Component Finish

Solder Alloy_Component Finish	beta	N63	R^2	failed	samples
▲ SAC305_SnPb	1.88	2132	69.9%	44	45
■ SN100C_SnPb	1.42	1393	93.5%	25	25
● SnPb_SnPb	11.62	2536	90.7%	25	25
▲ SAC305_SAC405	10.3	3367	91.4%	60	65
■ SN100C_SAC405	2.27	4982	57.0%	51	65
● SnPb_SAC405	1.49	4649	95.7%	24	44

Figure 34: PBGA-225 Weibull Plot for Immersion Silver PWB Finish

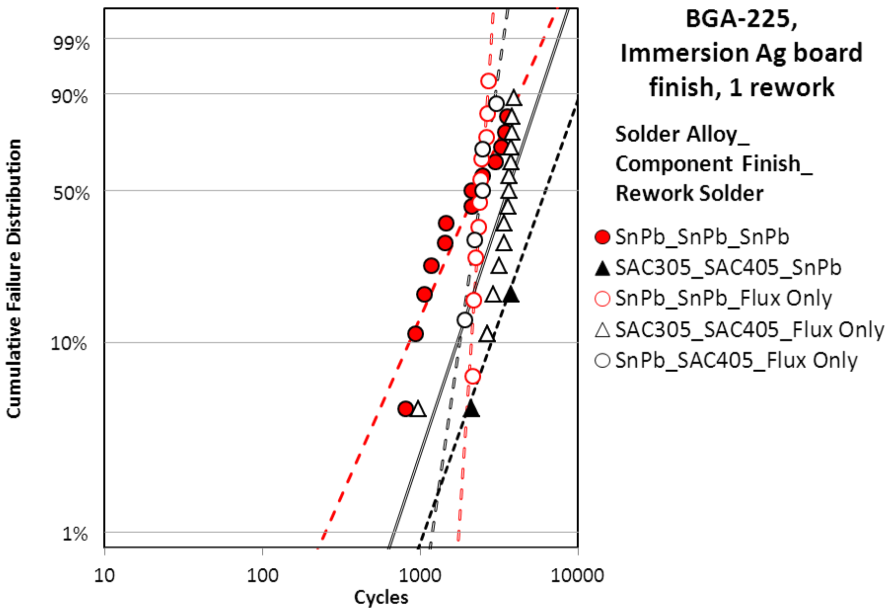


BGA-225, ENIG
board finish

Solder Alloy_
Component Finish

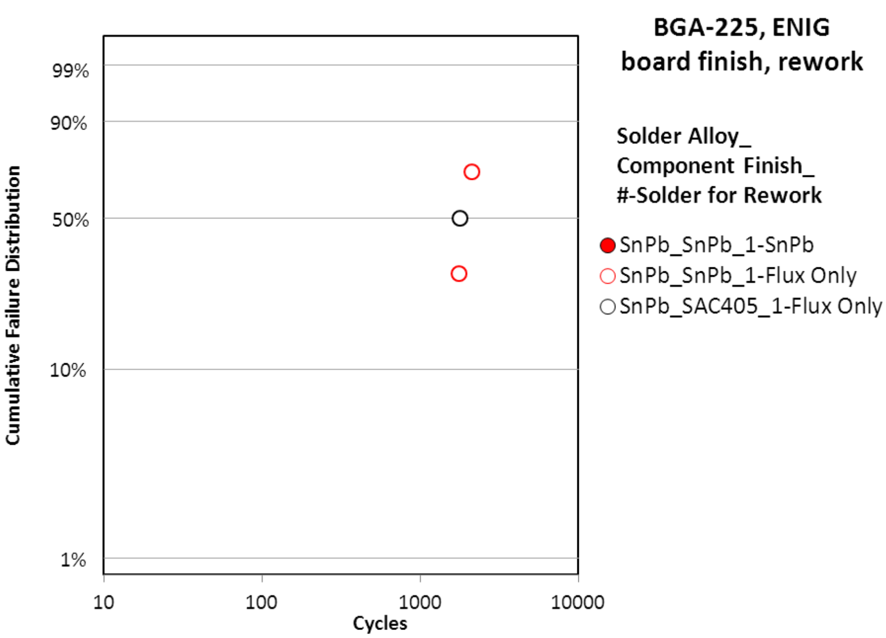
Solder Alloy_Component Finish	beta	N63	R^2	failed	samples
▲ SAC305_SnPb	0.55	4086	90.9%	3	5
▲ SAC305_SAC405	4.74	4291	89.9%	3	5
● SnPb_SAC405	n/a	n/a	n/a	1	4

Figure 35: PBGA-225 Weibull Plot for ENIG PWB Finish



beta	N63	R^2	failed	samples
1.93	2737	92.3%	13	15
2.4	7237	91.5%	3	15
12.89	2512	92.9%	10	10
2.56	4118	69.8%	14	15
5.91	2604	94.7%	5	5

Figure 36: Reworked PBGA-225 Weibull Plot for Immersion Silver Finish



beta	N63	R^2	failed	samples
n/a	n/a	n/a	0	3
n/a	n/a	n/a	2	2
n/a	n/a	n/a	1	1

Figure 37: Reworked PBGA-225 Weibull Plot for ENIG PWB Finish

Physical Failure Analysis

Metallographic cross-sectional analysis was conducted on the PBGA-225 components to document the solder joint failure location, crack morphology and solder joint microstructure. A significant amount of physical failure analysis was conducted on the PBGA-225 rework test vehicles. General physical failure observations of the failed PBGA-225 components were:

- The cracks in the solder joints initiated at the solder joint/component pad interface. The crack formation and location are in agreement with industry knowledge of PBGA failure modes [8][9].
- The solder joint geometries and wetting angles were acceptable and met industry workmanship criteria. There were a number of instances where voids were observed in the solder joints but their presence was not detrimental to the solder joint integrity.
- The manufactured test vehicle solder joint microstructures were homogenous with no segregation regions and the solder ball alloy (i.e. SnPb or SAC405) dominated the microstructure as it provided the largest material contribution to the solder joint formation. Some instances of large intermetallic compound (IMC) phases were observed but they typically have minimal interaction with the crack failure path.
- The reworked test vehicle solder joint microstructures had a number of mixed metallurgy cases where the solder joint was not homogenous. These solder joints tended to fail at the solder joint/test vehicle pad interface with lead (Pb) segregated in the crack interface. This failure mode previously documented in the JCAA/JGPP testing program [1].

Figure 38 thru Figure 47 illustrate the typical PBGA-225 solder joint failures observed:

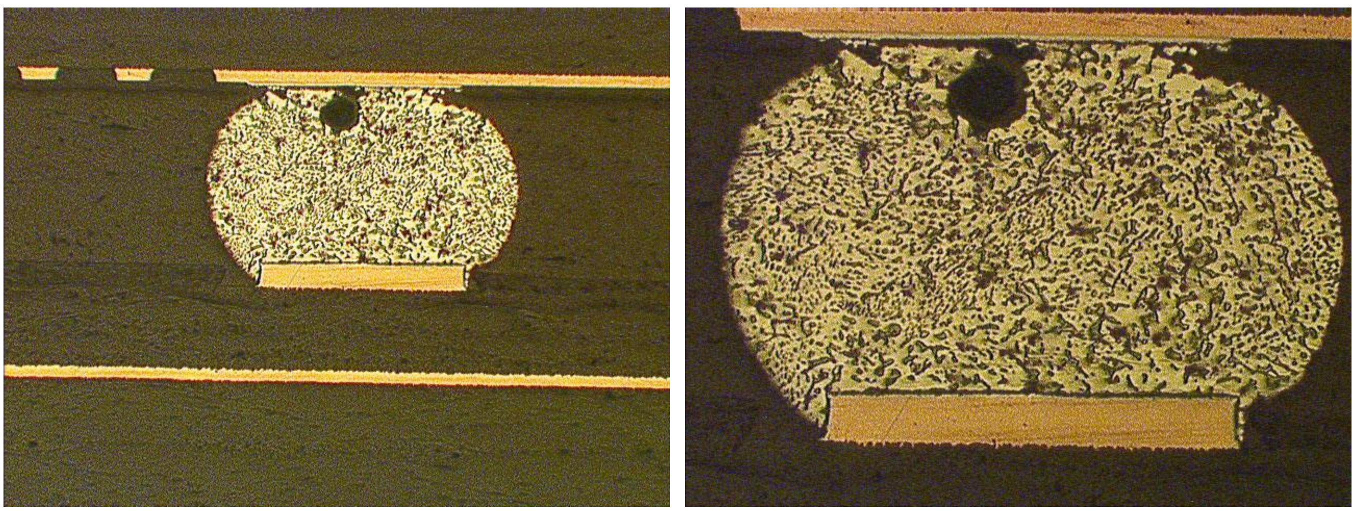


Figure 38: PBGA-225 Solder Joints, Board 8, Component U5, SnPb/SnPb, Failed @ 2431 Cycles

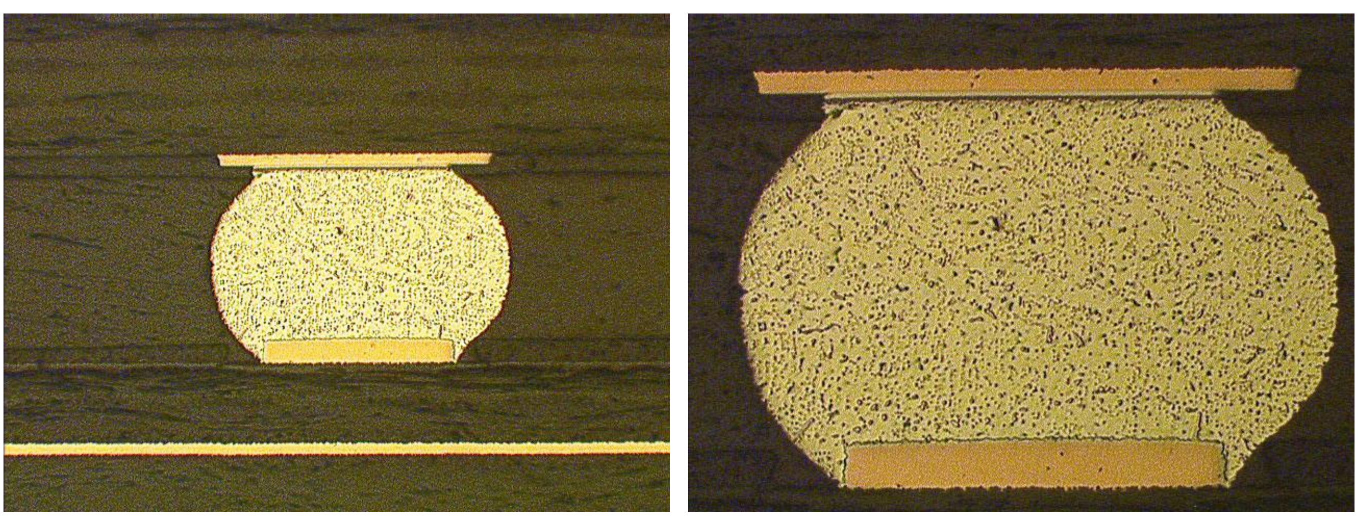


Figure 39: PBGA-225 Solder Joints, Board 127, Component U5, SnPb/SAC405, DNF

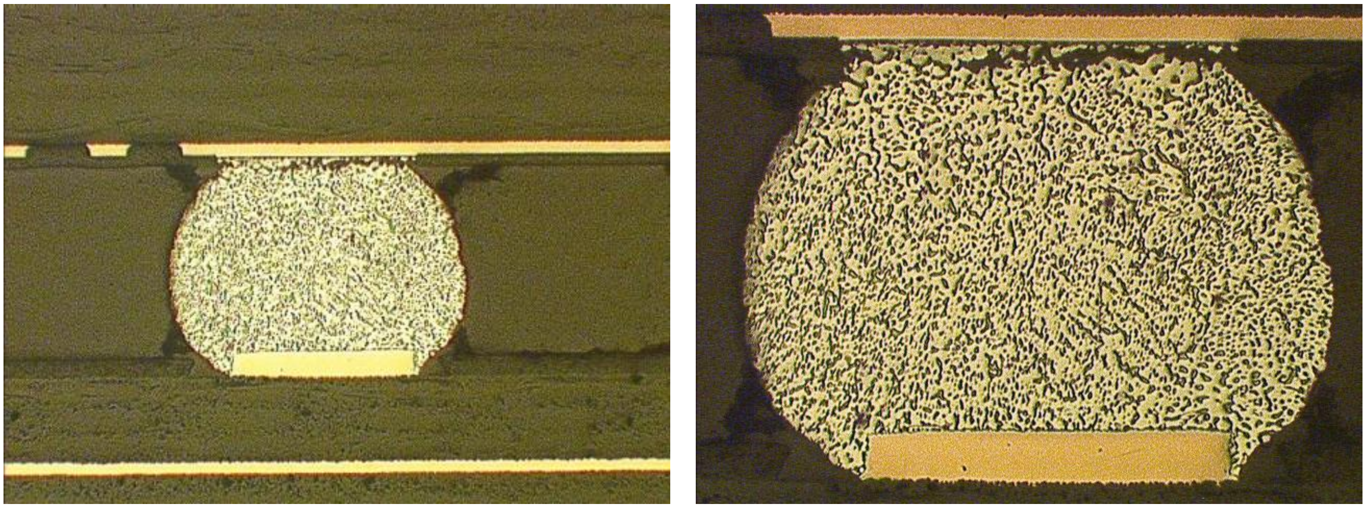


Figure 40: PBGA-225 Solder Joints, Board 168, Component U5, SAC305/SnPb, Failed @ 1926 Cycles

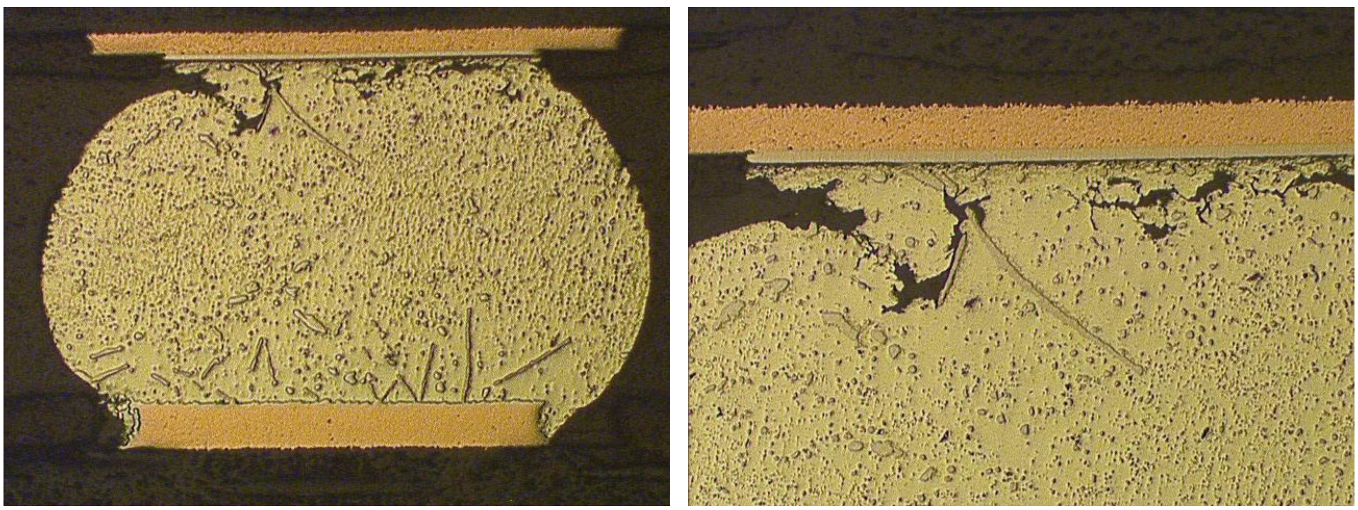


Figure 41: PBGA-225 Solder Joints, Board 49, Component U6, SAC305/SAC405, Failed @ 2763 Cycles

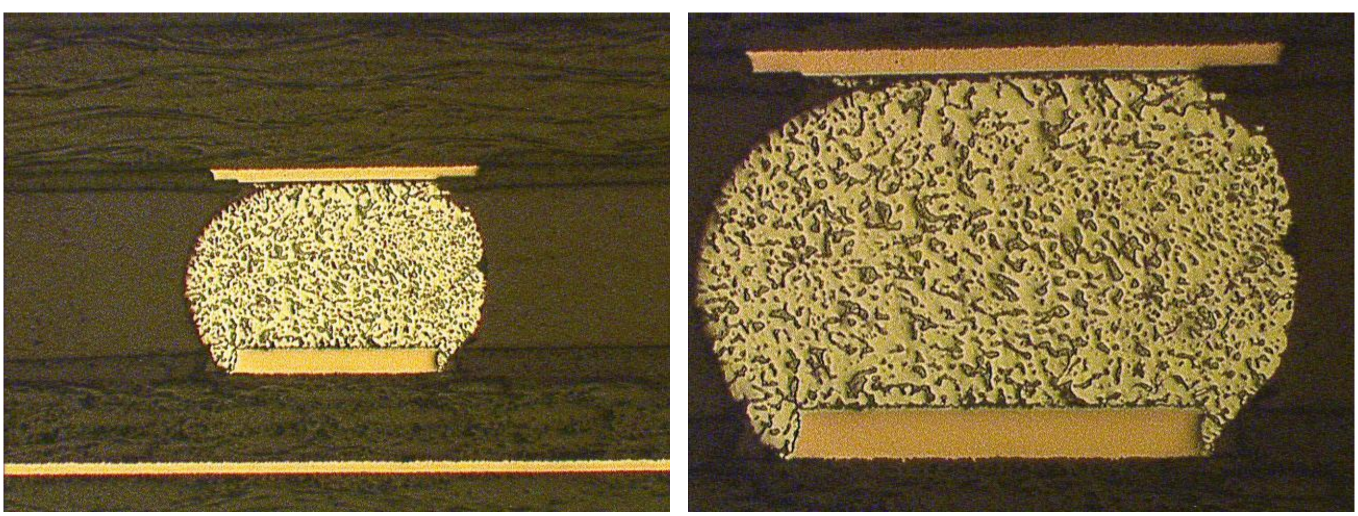


Figure 42: PBGA-225 Solder Joints, Board 106, Component U55, SN100C/SnPb, Failed @ 1064 Cycles

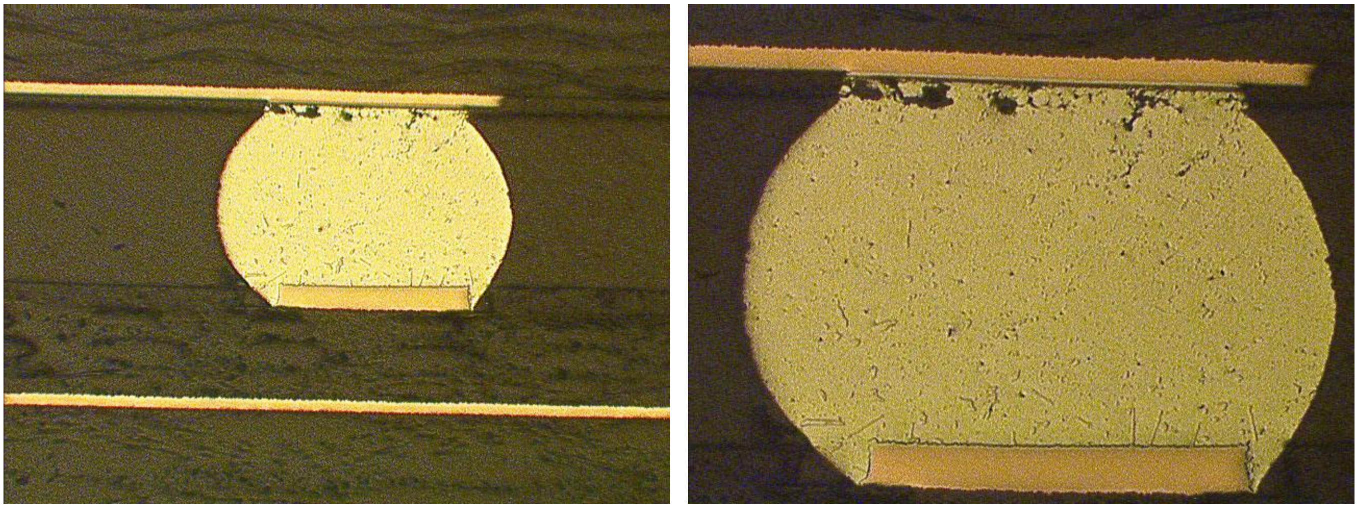


Figure 43: PBGA-225 Solder Joints, Board 104, Component U21, SN100C/SAC405, Failed @ 3812 Cycles

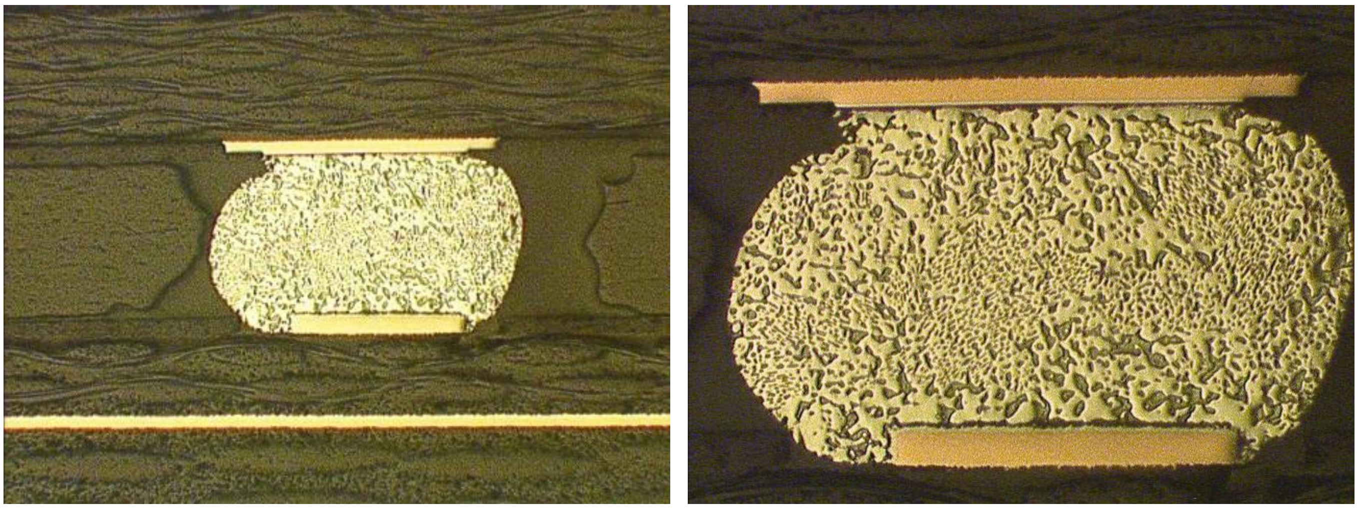


Figure 44: Reworked PBGA-225 Solder Joints, Board 127, Component U56, Initially SnPb/SnPb, 1 rework Flux Only/SnPb, Failed @ 2349 Cycles

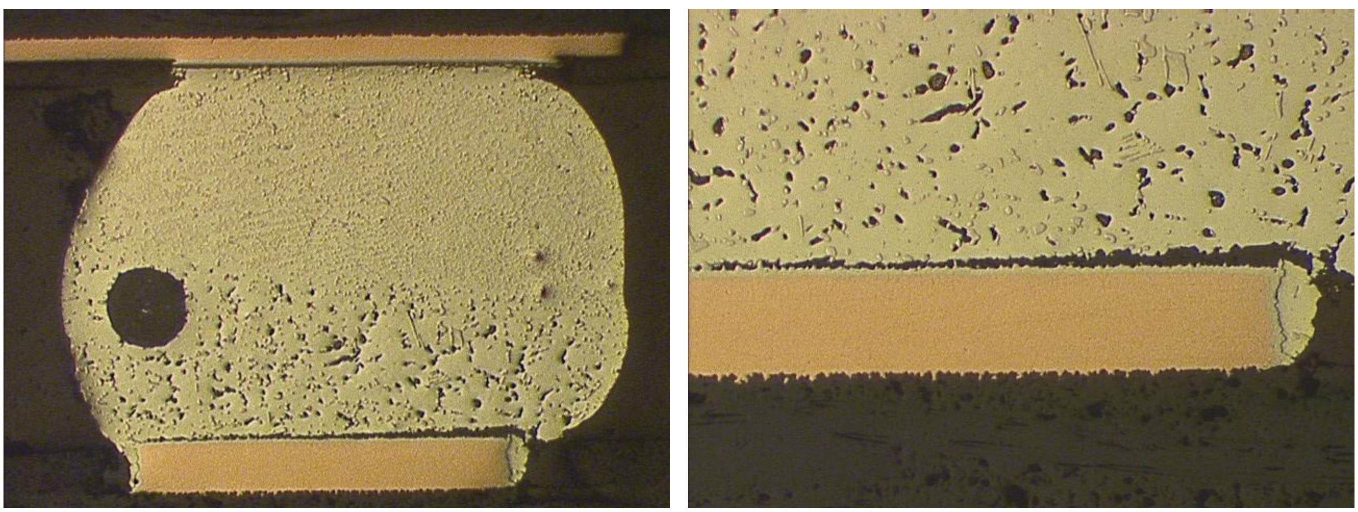


Figure 45: Reworked PBGA-225 Solder Joints, Board 124, Component U6, Initially SnPb/SnPb, 1 rework SnPb/SAC405, Failed @ 2137 Cycles

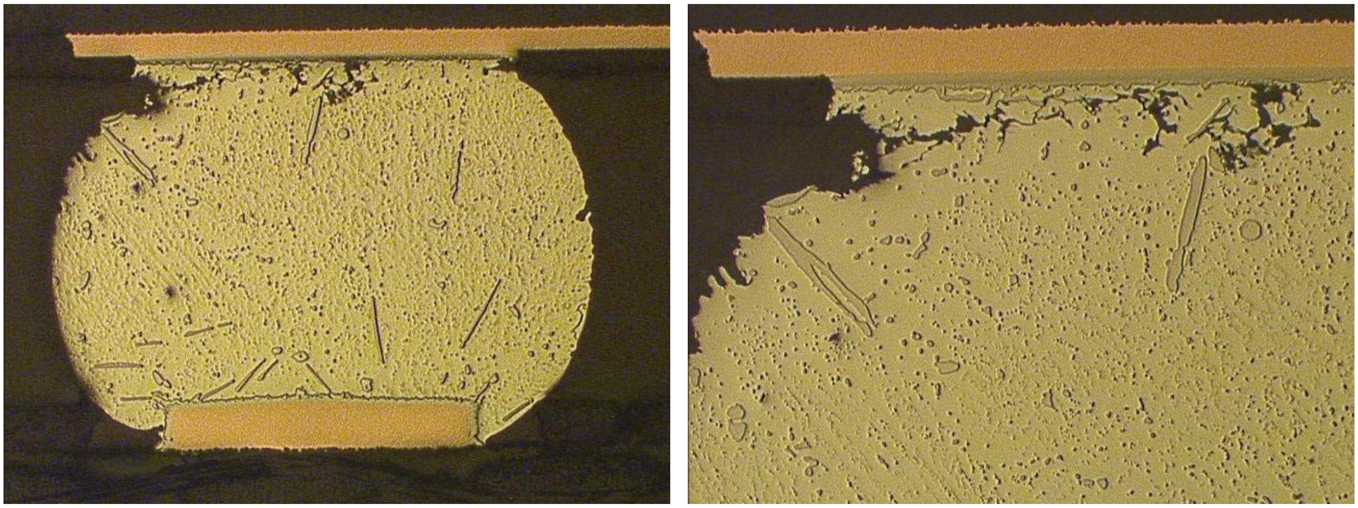


Figure 46: Reworked PBGA-225 Solder Joints, Board 127, Component U56, Initially SAC305/SAC405, 1 rework Flux Only/SAC405, Failed @ 2349 Cycles

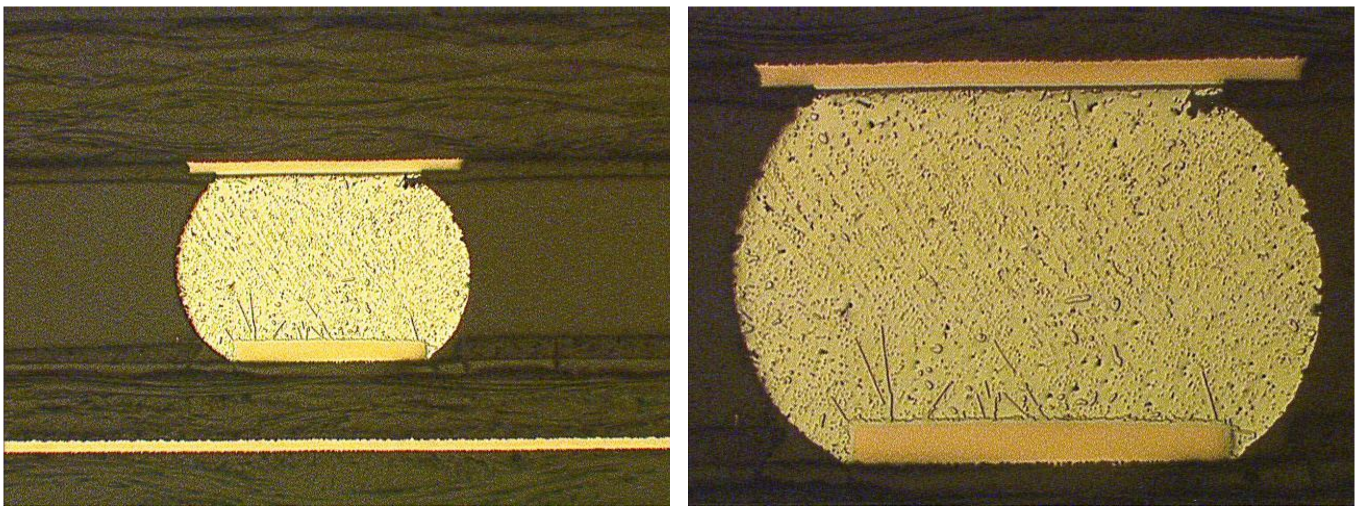


Figure 47: Reworked PBGA-225 Solder Joints, Board 164, Component U18, Initially SAC305/SAC405, 1 rework SnPb/SAC405, DNF

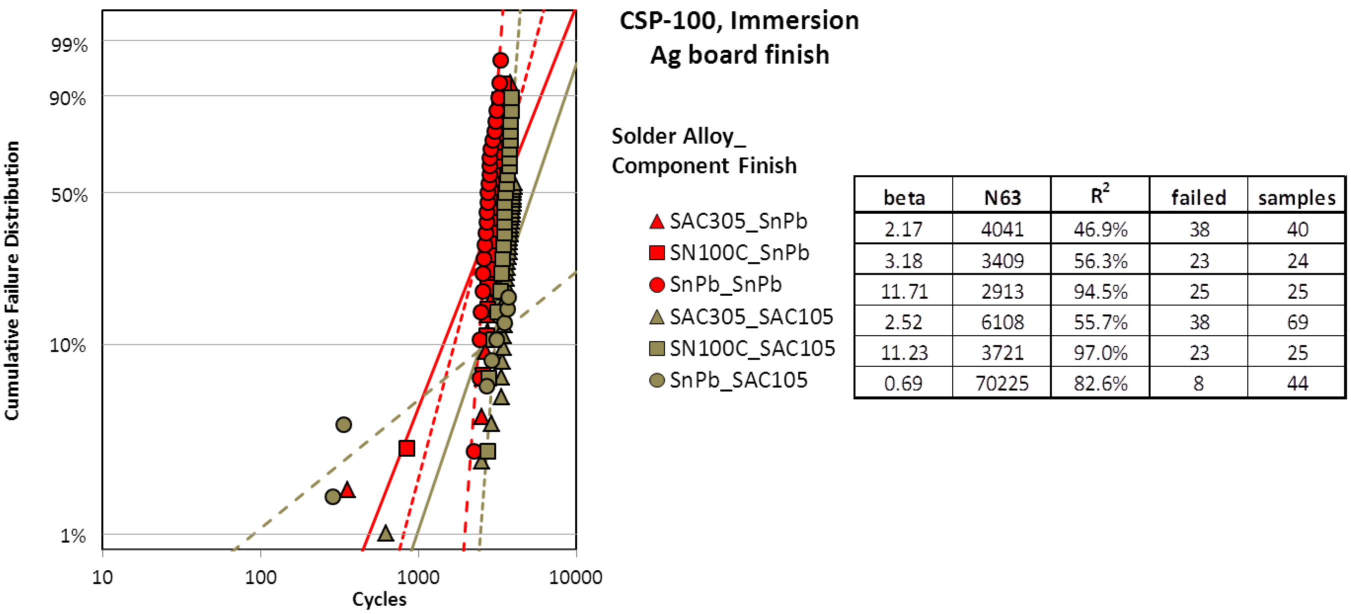
Chip Scale Package (CSP-100) Results

Statistical Analysis

The CSP-100 components had accumulated 68% population failure after the completion of 4068 thermal cycles. CSP-100 components had six different combinations (SAC/SAC105, SAC/SnPb, SN100C/SAC105, SN100C/SnPb, SnPb/SAC105, SnPb/SnPb) tested.
The solder alloy/component finish combinations were statistically indistinguishable from each other thus no best performing combination was identified. There were a few early failures but overall the results populations were consistent. The SnPb/SAC105 combination did not have sufficient failures to calculate a valid N63 metric although the lack of failures is a good indication of its thermal cycle solder joint integrity robustness. The number of solder joint failures for the ENIG test vehicles was very small and therefore no conclusions were made.

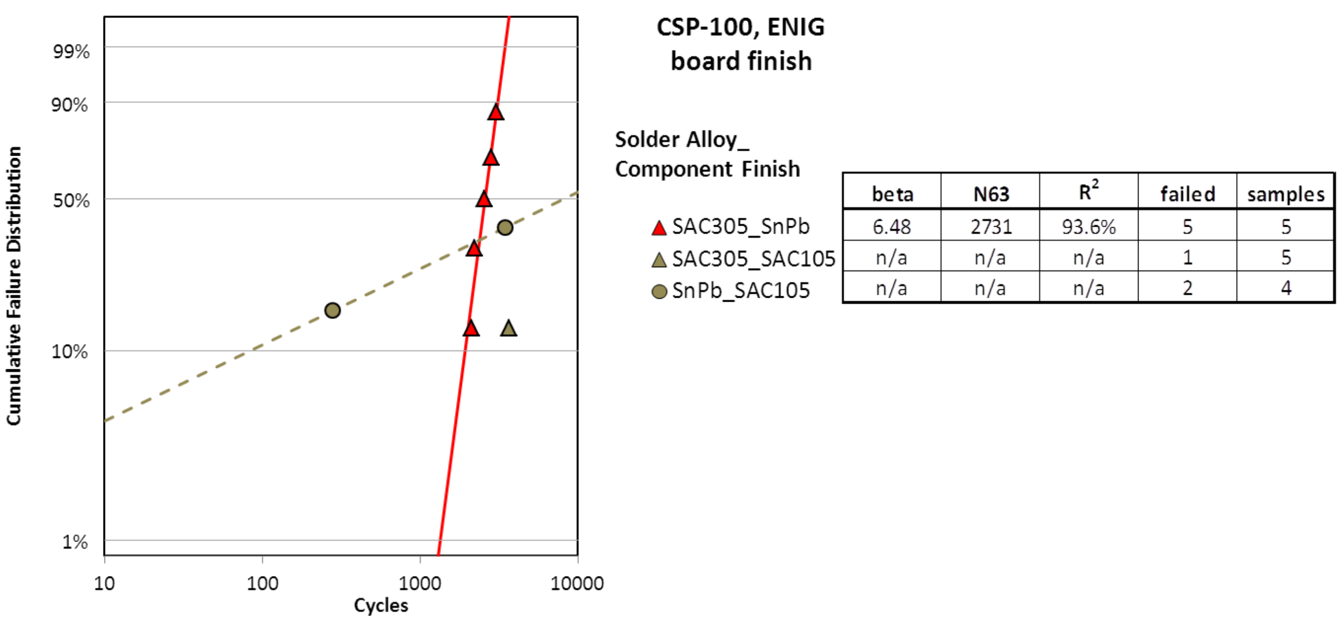
The reworked CSP-100 components had accumulated only 37% population failure after the completion of 4068 thermal cycles. One clear result during the CSP-100 rework process was the impact of using the flux only procedure in comparison to the solder paste procedure. Similar to the reworked BGA flux only procedure, the CSP-100 components reworked with the flux only procedure were not as robust to thermal cycling as the solder paste procedure. It is hypothesized that the smaller solderball diameter of the CSP-100 exacerbates any coplanarity differences in the component solderball array impacting solder joint integrity.

The Weibull plots in Figure 48 through Figure 51 summarize the CSP-100 thermal cycle test results.



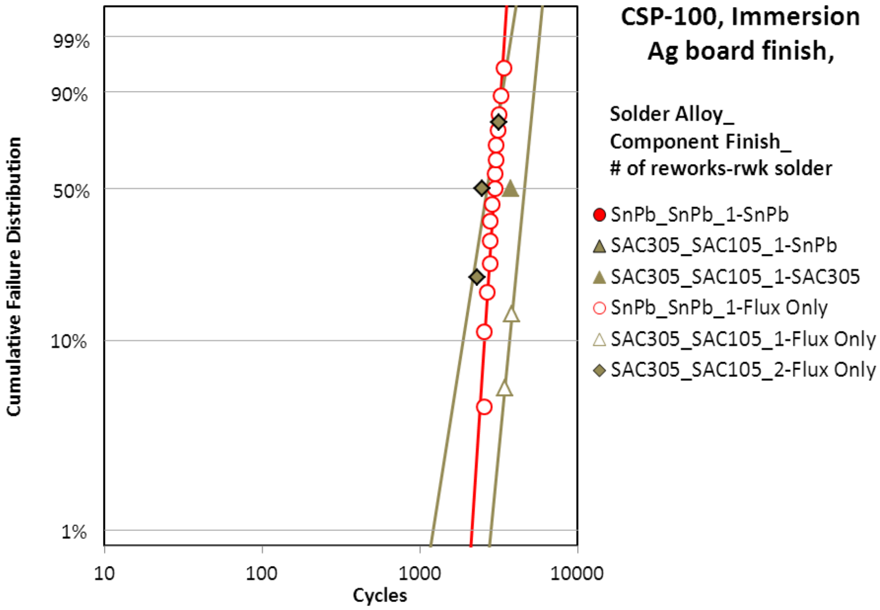
beta	N63	R^2	failed	samples
2.17	4041	46.9%	38	40
3.18	3409	56.3%	23	24
11.71	2913	94.5%	25	25
2.52	6108	55.7%	38	69
11.23	3721	97.0%	23	25
0.69	70225	82.6%	8	44

Figure 48: CSP-100 Weibull Plot for Immersion Silver PWB Finish



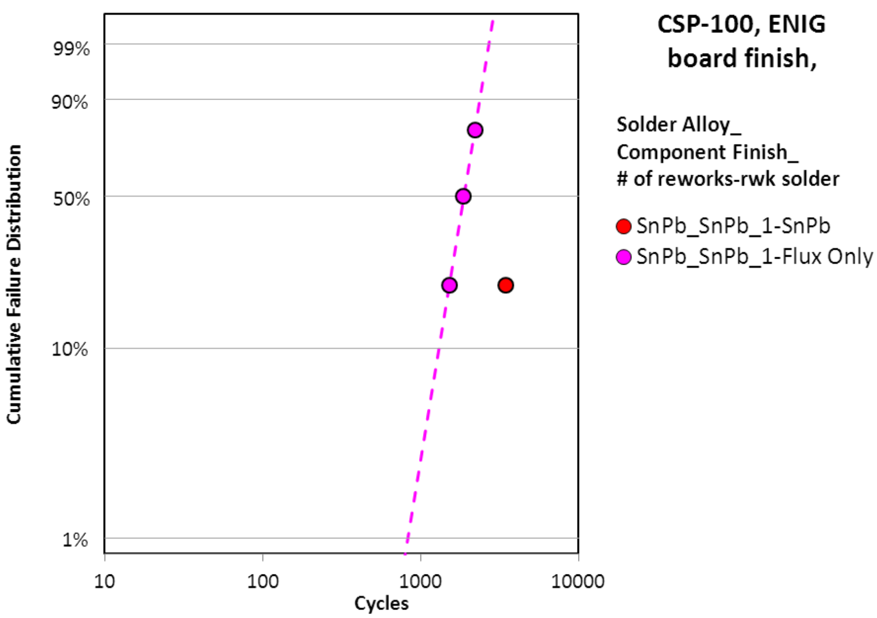
beta	N63	R^2	failed	samples
6.48	2731	93.6%	5	5
n/a	n/a	n/a	1	5
n/a	n/a	n/a	2	4

Figure 49 CSP-100 Weibull Plot for ENIG PWB Finish



beta	N63	R^2	failed	samples
n/a	n/a	n/a	0	15
n/a	n/a	n/a	0	15
n/a	n/a	n/a	1	1
12.87	3059	94.5%	15	15
n/a	n/a	n/a	2	12
5.38	2858	86.6%	3	3

Figure 50 Reworked CSP-100 Weibull Plot for Immersion Silver PWB Finish



beta	N63	R^2	failed	samples
n/a	n/a	n/a	1	3
5.18	2020	100.0%	3	3

Figure 51 Reworked CSP-100 Weibull Plot for ENIG PWB Finish

Physical Failure Analysis

Metallographic cross-sectional analysis was conducted on the CSP-100 components to document the solder joint failure location, crack morphology and solder joint microstructure. A significant amount of physical failure analysis was conducted on the CSP-100 rework test vehicles. General physical failure observations of the failed CSP-100 components were:

- The cracks in the solder joints were observed to have two failure modes: (1) initiation at the solder joint/component pad interface; (2) significant solder ball deformation with cracks at either solder joint component pad or solder joint/test vehicle pad interface.
- The solder joint geometries and wetting angles were acceptable and met industry workmanship criteria. There were a number of instances where voids were observed in the solder joints but their presence was not detrimental to the solder joint integrity.
- The manufactured test vehicle solder joint microstructures were homogenous with no segregation regions and the solder ball alloy (i.e. SnPb or SAC405) dominated the microstructure as it provided the largest material contribution to solder joint formation. All of the CSP-100 solder microstructures had significant shear deformation. The SnPb solder alloy solder joints had readily apparent regions of grain coarsening and the Lead-free solder alloys had significant "spider web cracking" and joint deformation.
- The reworked test vehicle solder joint microstructures did not appear to be different than the as–manufactured solder joint microstructures.

Figure 52 thru Figure 61 illustrate the typical PBGA-225 solder joint failures observed:

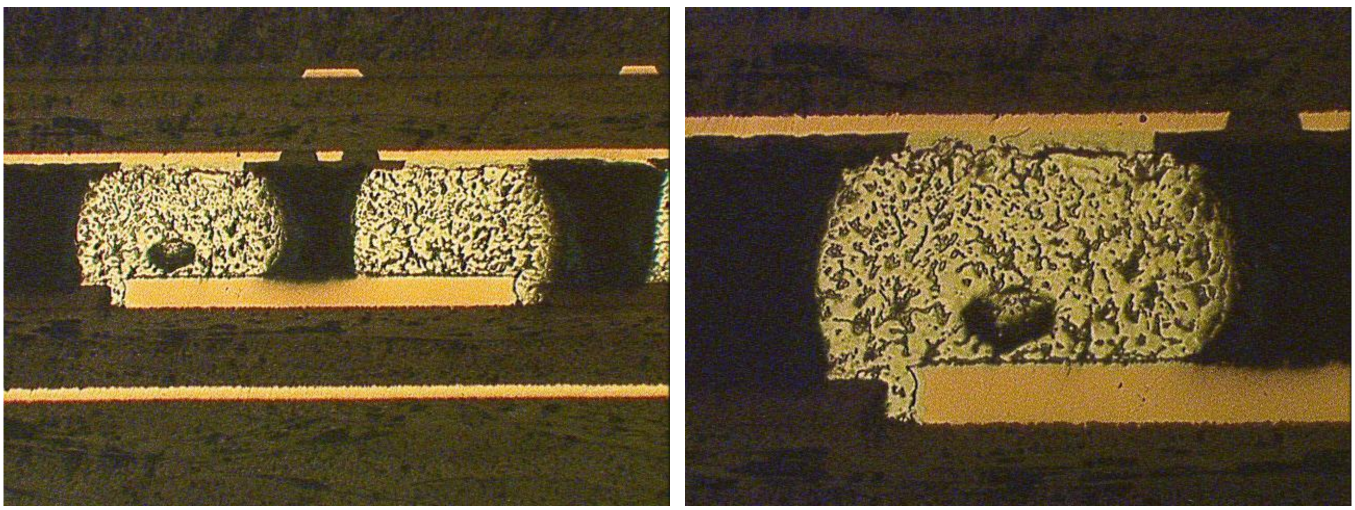


Figure 52: CSP-100 Solder Joints, Board 7, Component U37, SnPb/SnPb, Failed @ 2837 Cycles

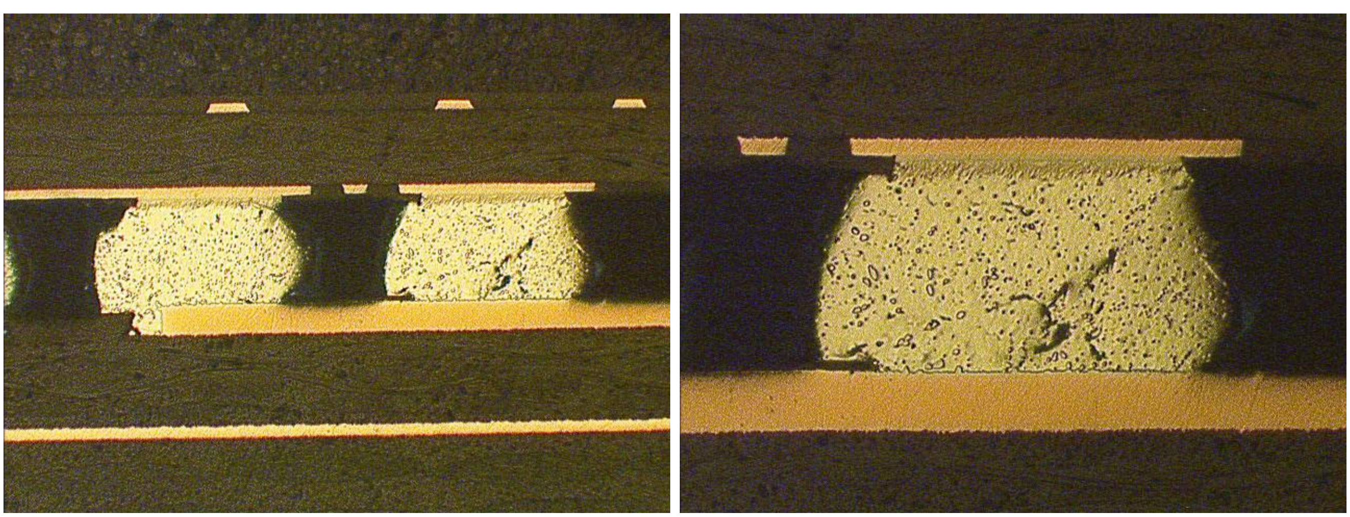


Figure 53: CSP-100 Solder Joints, Board 124, Component U32, SnPb/SAC105, Failed @ 287 Cycles

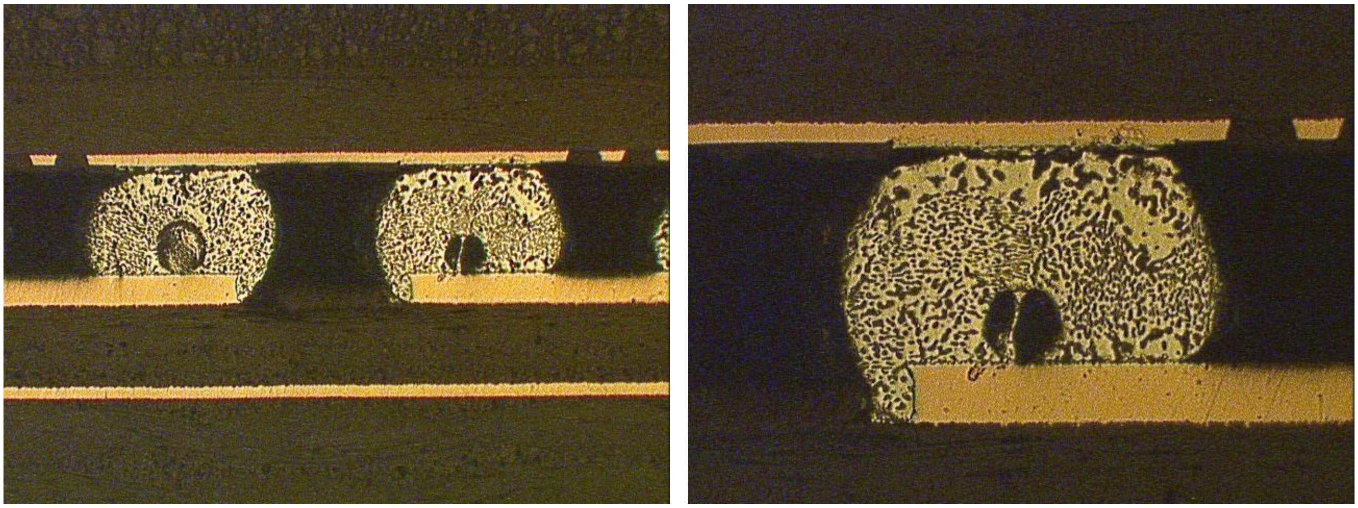


Figure 54: CSP-100 Solder Joints, Board 166, Component U32, SAC305/SnPb, Failed @ 3417 Cycles

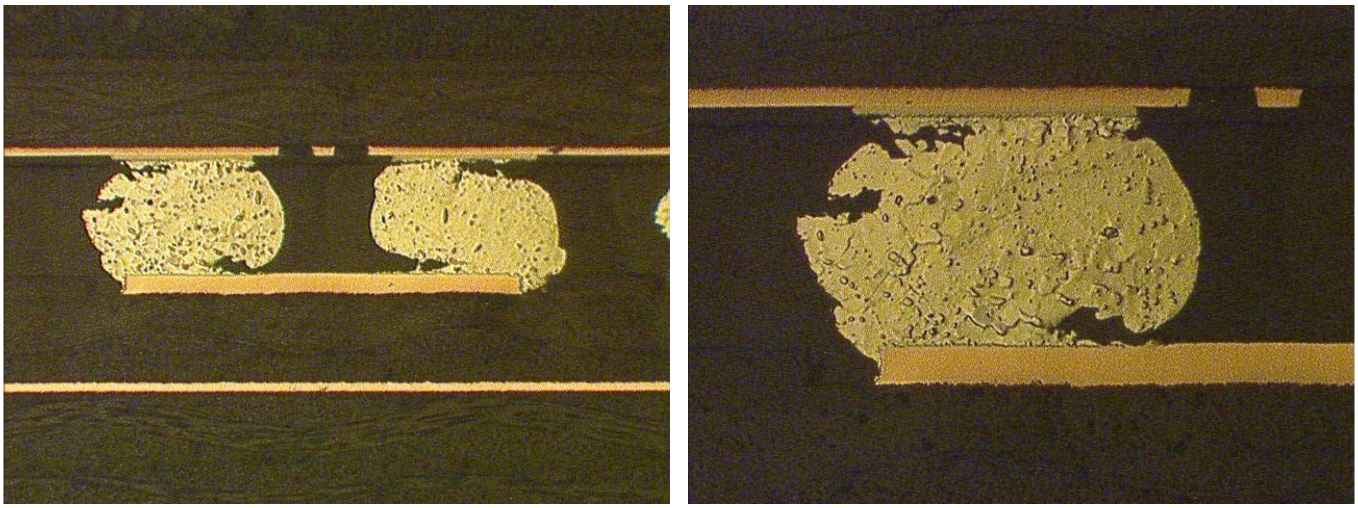


Figure 55: CSP-100 Solder Joints, Board 49, Component U60, SAC305/SAC105, Failed @ 3908 Cycles

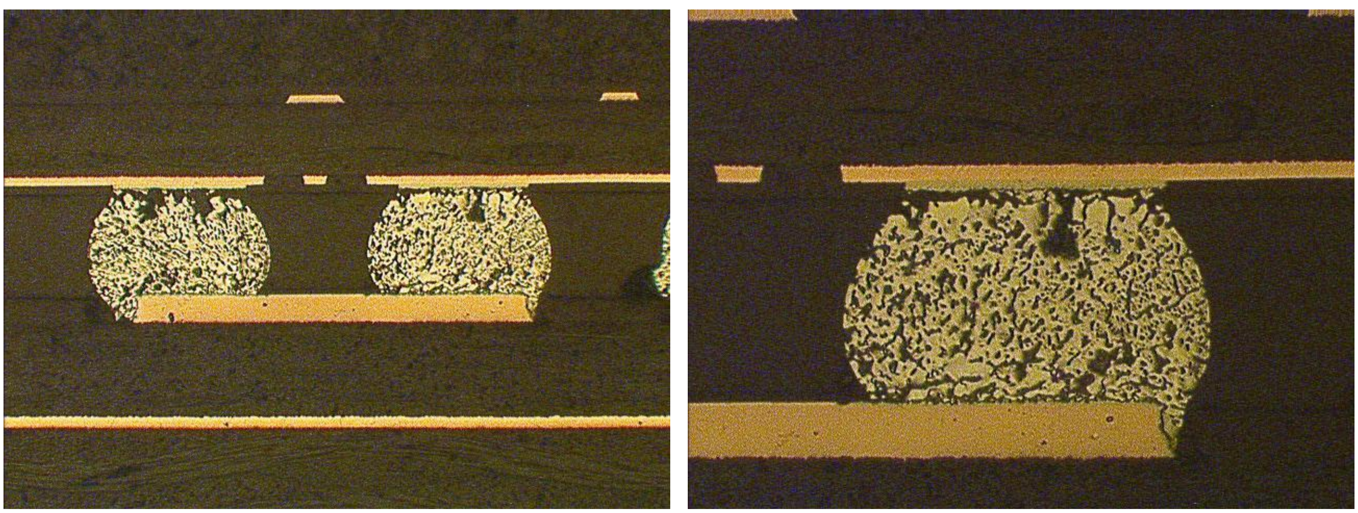


Figure 56: CSP-100 Solder Joints, Board 103, Component U33, SN100C/SnPb, Failed @ 2932 Cycles

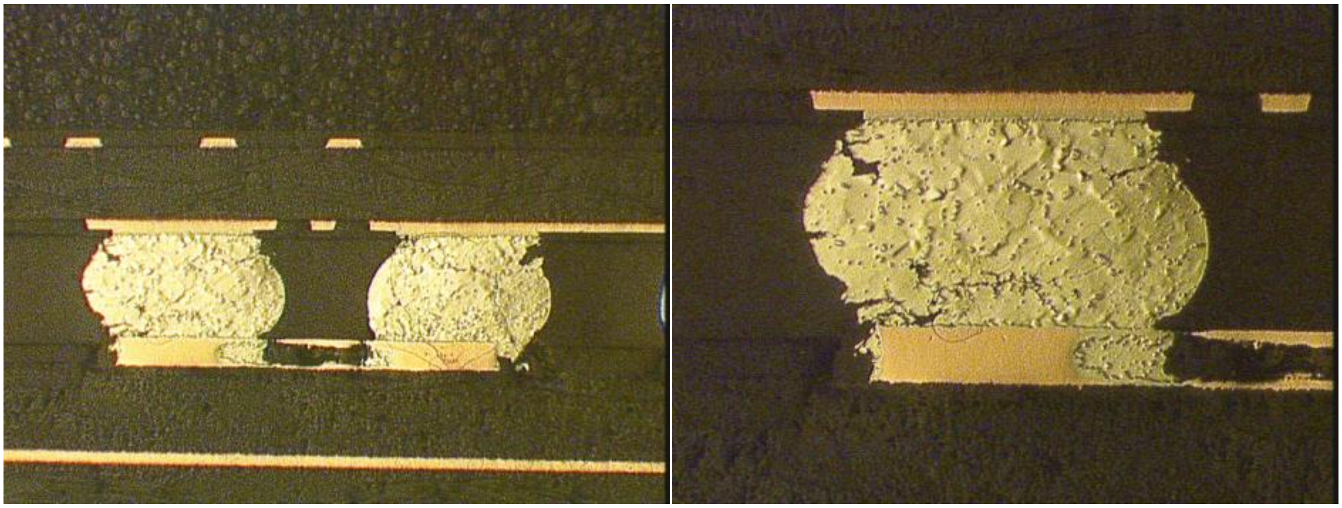


Figure 57: CSP-100 Solder Joints, Board 106, Component U36, SN100C/SAC105, Failed @ 3908 Cycles

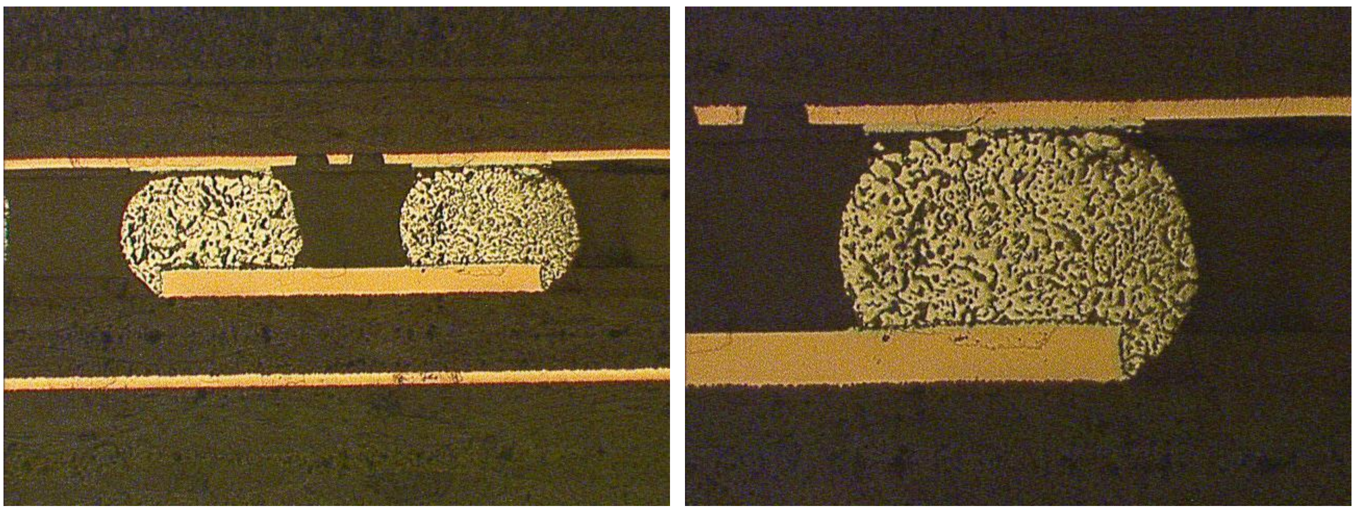


Figure 58: Reworked CSP-100 Solder Joints, Board 128, Component U19, Initially SnPb/SnPb, 1 rework Flux Only/SnPb, Failed @ 3012 Cycles

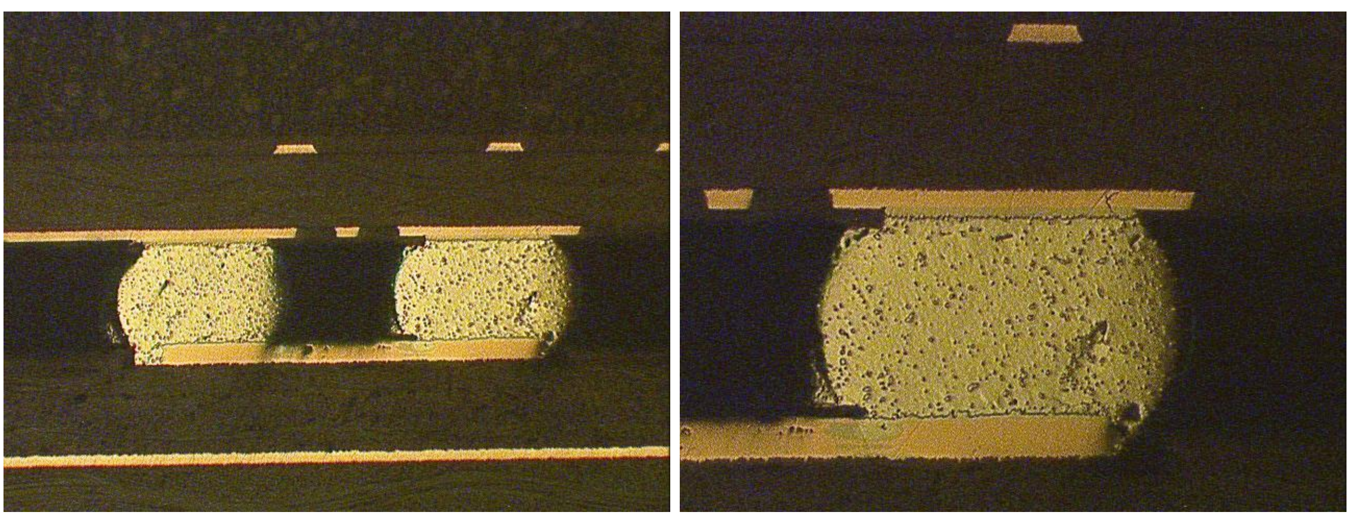


Figure 59: Reworked CSP-100 Solder Joints, Board 126, Component U60, Initially SnPb/SnPb, 1 rework SnPb/SAC105, DNF

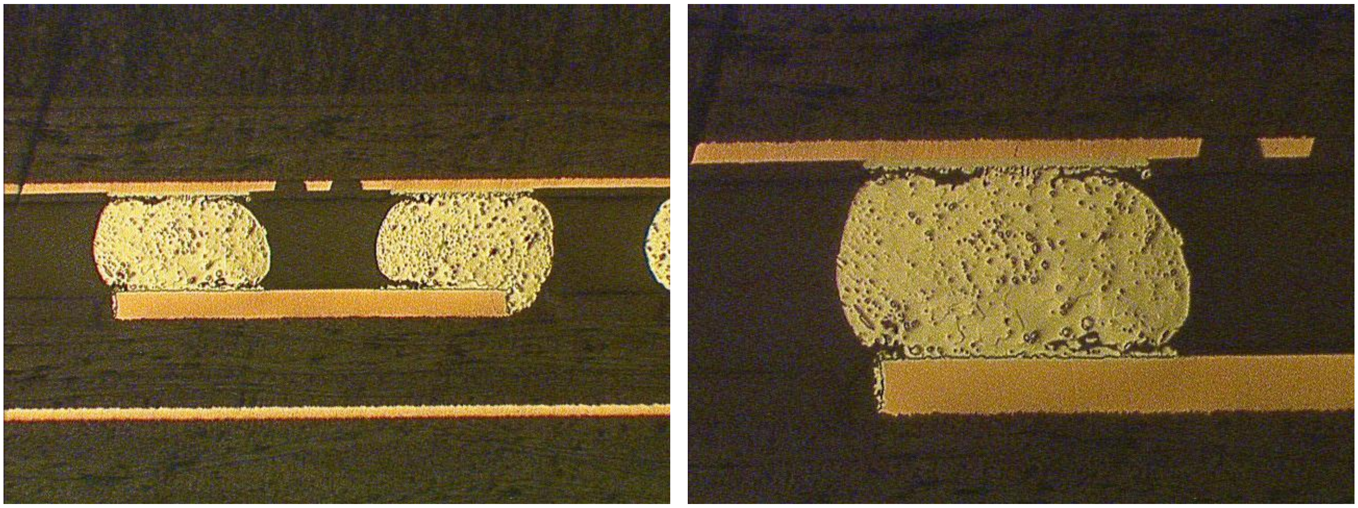


Figure 60: Reworked CSP-100 Solder Joints, Board 168, Component U19, Initially SAC305/SAC105, 1 rework Flux Only/SAC105, DNF

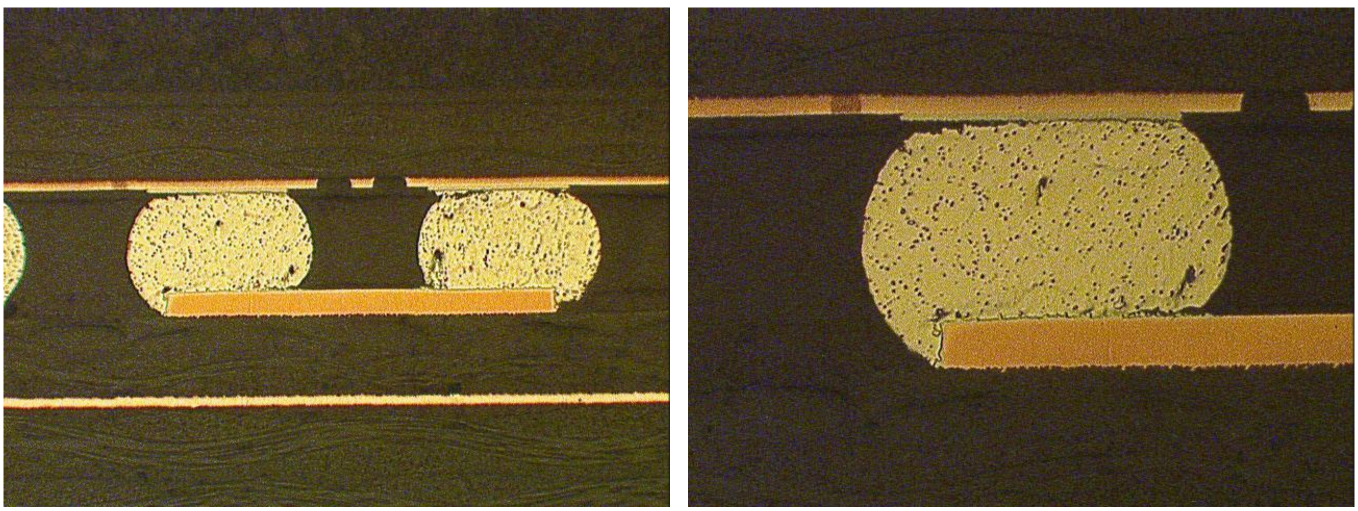


Figure 61: Reworked CSP-100 Solder Joints, Board 164, Component U33, Initially SAC305/SAC105, 1 rework SnPb/SAC105, DNF

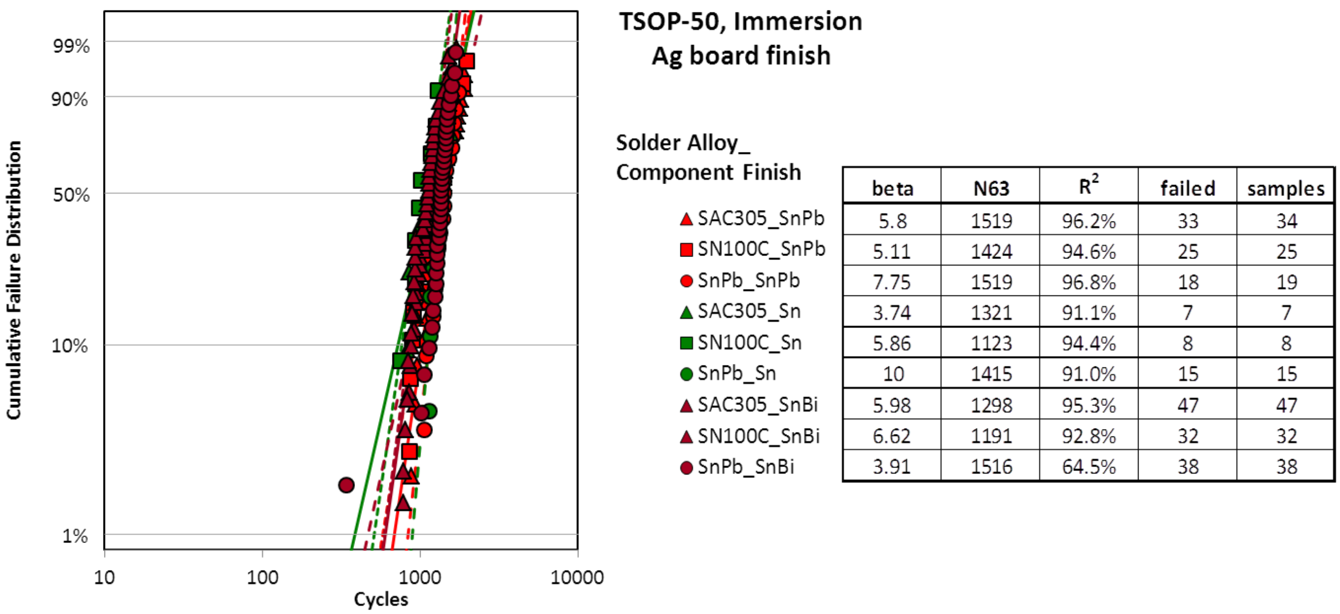
Thin Small Outline Package (TSOP-50) Results

Statistical Analysis

The TSOP-50 components had accumulated 99% population failure after the completion of 4068 thermal cycles. TSOP-50 components had nine different combinations (SAC/SnPb, SAC/SnBi, SAC/Sn, SN100C/SnPb, SN100C/SnBi, SN100C/Sn, SnPb/SnBi, SnPb/Sn, SnPb/SnPb) tested. This result is not surprising as TSOP components which use an Alloy 42 lead material are known to have solder joint integrity issues in High Performance electronics applications [10]. The solder alloy/component finish combinations were statistically indistinguishable from each other thus no best performing combination was identified. The results populations were very consistent. The number of solder joint failures for the ENIG test vehicles was very small and therefore no conclusions were made.

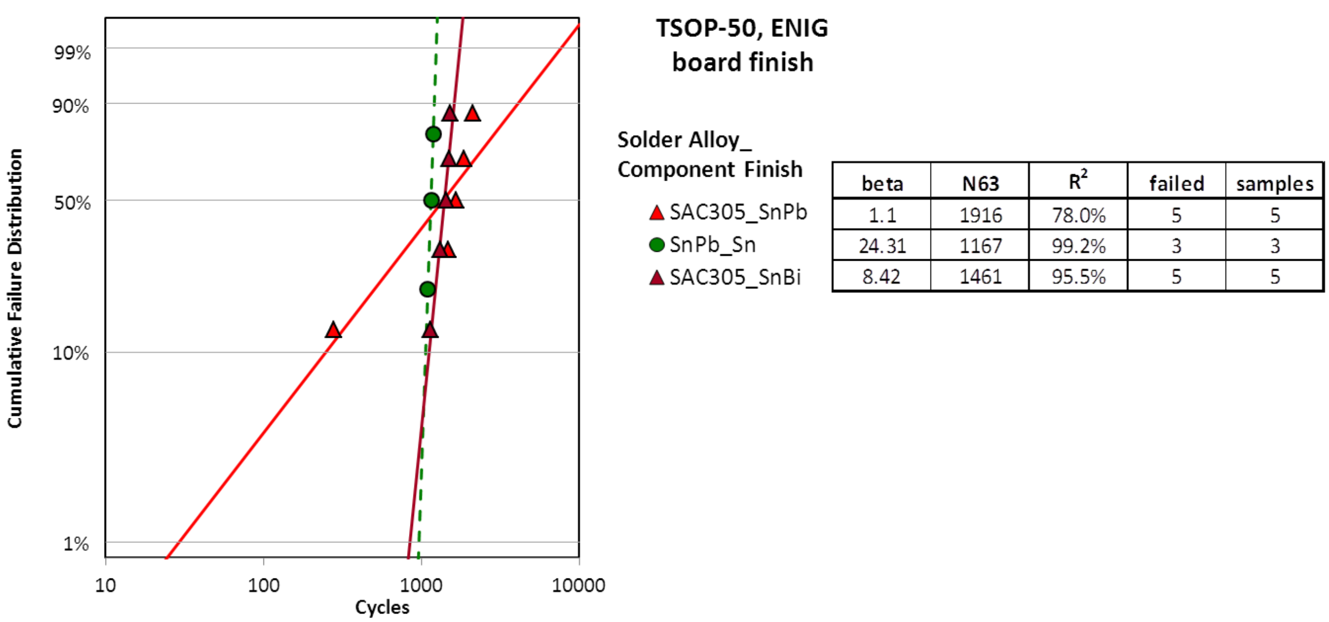
The reworked TSOP-50 components had accumulated 100% population failure after the completion of 4068 thermal cycles. The results show that no preferred alloy/component finish combination could be selected from the data as the combination populations were statistically indistinguishable from each other for both the 1 Rework and 2 Rework cases.

The Weibull plots in Figure 62 through Figure 64 summarize the TSOP-50 thermal cycle test results.



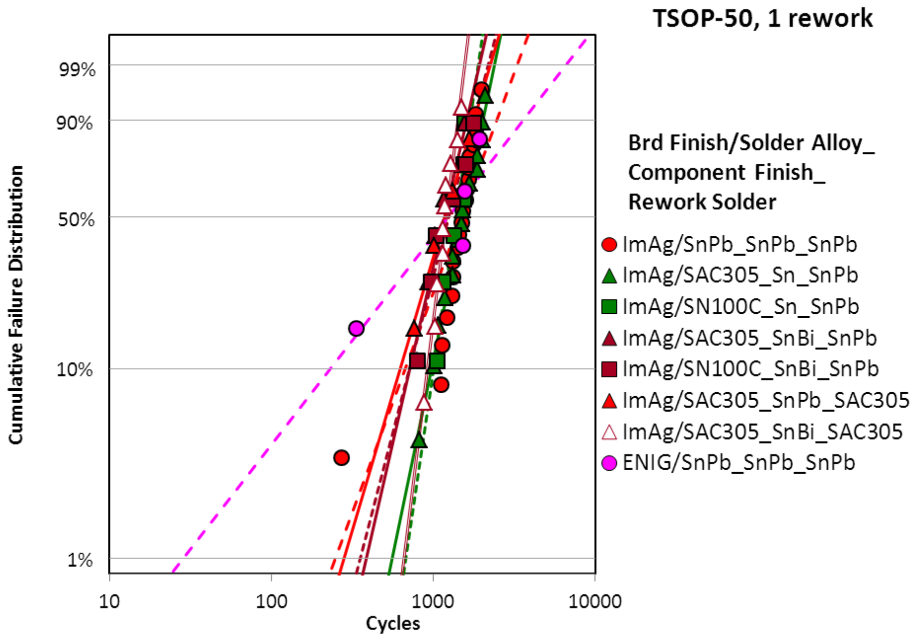
Solder Alloy_ Component Finish	beta	N63	R^2	failed	samples
SAC305_SnPb	5.8	1519	96.2%	33	34
SN100C_SnPb	5.11	1424	94.6%	25	25
SnPb_SnPb	7.75	1519	96.8%	18	19
SAC305_Sn	3.74	1321	91.1%	7	7
SN100C_Sn	5.86	1123	94.4%	8	8
SnPb_Sn	10	1415	91.0%	15	15
SAC305_SnBi	5.98	1298	95.3%	47	47
SN100C_SnBi	6.62	1191	92.8%	32	32
SnPb_SnBi	3.91	1516	64.5%	38	38

Figure 62: TSOP-50 Weibull Plot for Immersion Silver PWB Finish



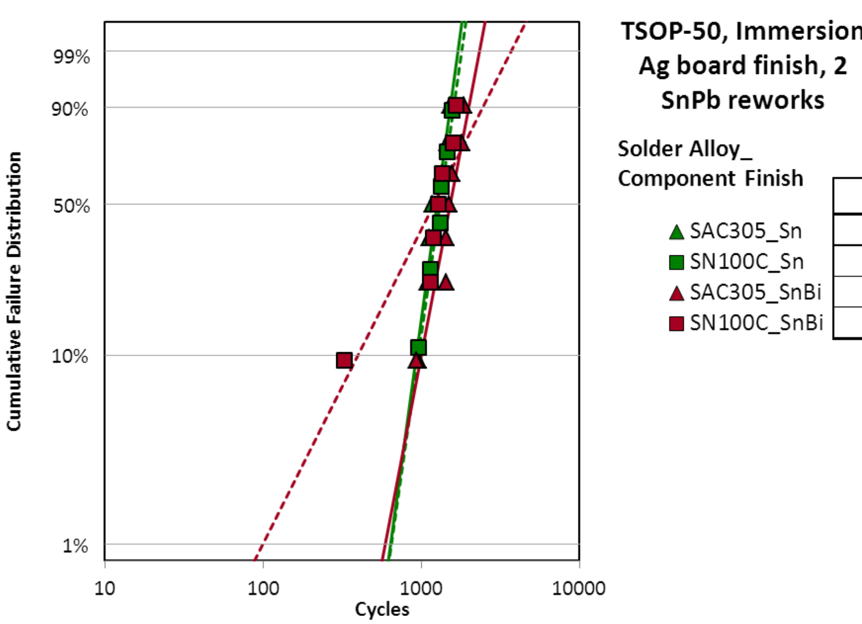
Solder Alloy_ Component Finish	beta	N63	R^2	failed	samples
SAC305_SnPb	1.1	1916	78.0%	5	5
SnPb_Sn	24.31	1167	99.2%	3	3
SAC305_SnBi	8.42	1461	95.5%	5	5

Figure 63: TSOP-50 Weibull Plot for ENIG PWB Finish



beta	N63	R^2	failed	samples
2.37	1739	70.4%	20	20
4.21	1670	98.3%	16	16
5.95	1470	90.8%	6	6
3.8	1294	93.0%	6	6
3.36	1395	95.3%	6	6
2.94	1348	99.1%	4	4
7.09	1265	96.4%	10	10
1.13	1709	81.5%	4	4

Figure 64 TSOP-50 Rework Weibull Plot for 1 Rework



beta	N63	R^2	failed	samples
6.25	1333	94.5%	7	7
5.98	1394	98.1%	6	6
4.47	1656	88.6%	7	7
1.7	1496	77.0%	7	7

Figure 65 TSOP-50 Rework Weibull Plot for 2 Rework

Physical Failure Analysis

Metallographic cross-sectional analysis was conducted on the TSOP-50 components to document the solder joint failure location, crack morphology and solder joint microstructure. General physical failure observations of the failed TSOP-50 components were:

- The cracks in the solder joints initiated in the heel fillet region and traversed under the foot towards the lead toe. The crack formation and location are in agreement with industry knowledge of Alloy 42 TSOP failure modes [10].
- The solder joint geometries and wetting angles were acceptable and met industry workmanship criteria (IPC-JSTD-001). There were a number of instances where the solder did flow into the upper lead bend region. In most cases this condition is acceptable per industry standards. However several solder joints, primarily reworked cases, were observed with excessive solder in the upper lead bend which violated industry standards. Rockwell Collins has conducted internal studies demonstrating that solder material located between the component lead and the component body does not cause solder joint integrity issues for plastic bodied components [13].
- The solder joint microstructures were reasonably homogenous with no segregation regions observed in the mixed metallurgy cases.

Figure 66 thru Figure 75 illustrate the typical TSOP-50 solder joint failures.

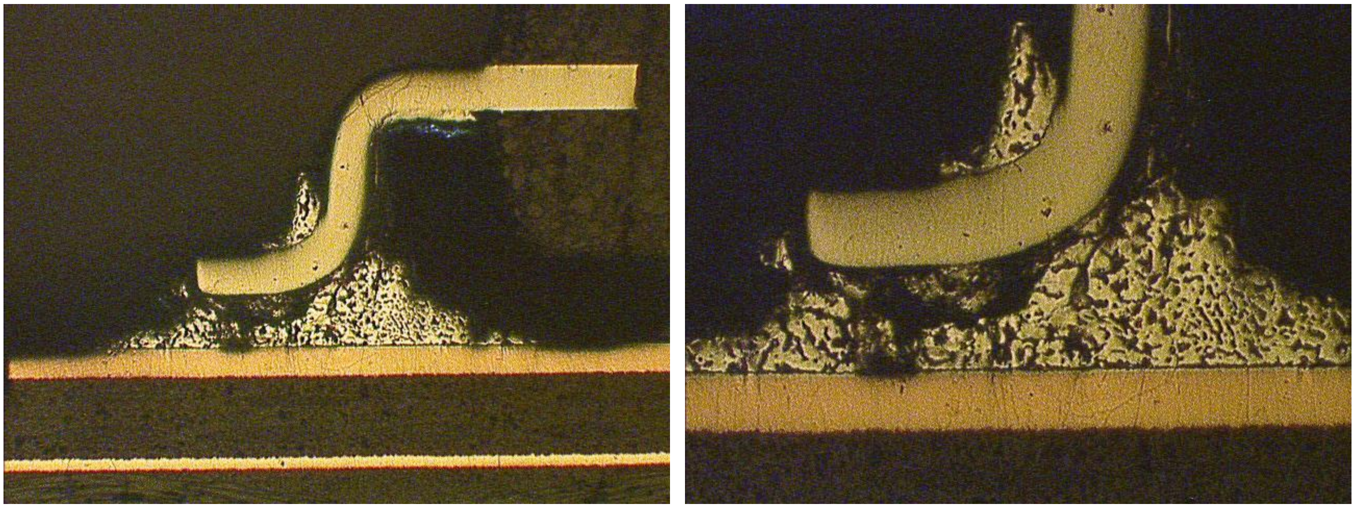


Figure 66: TSOP-50 Solder Joints, Board 8, Component U40, SnPb/SnPb, Failed @ 1252 Cycles

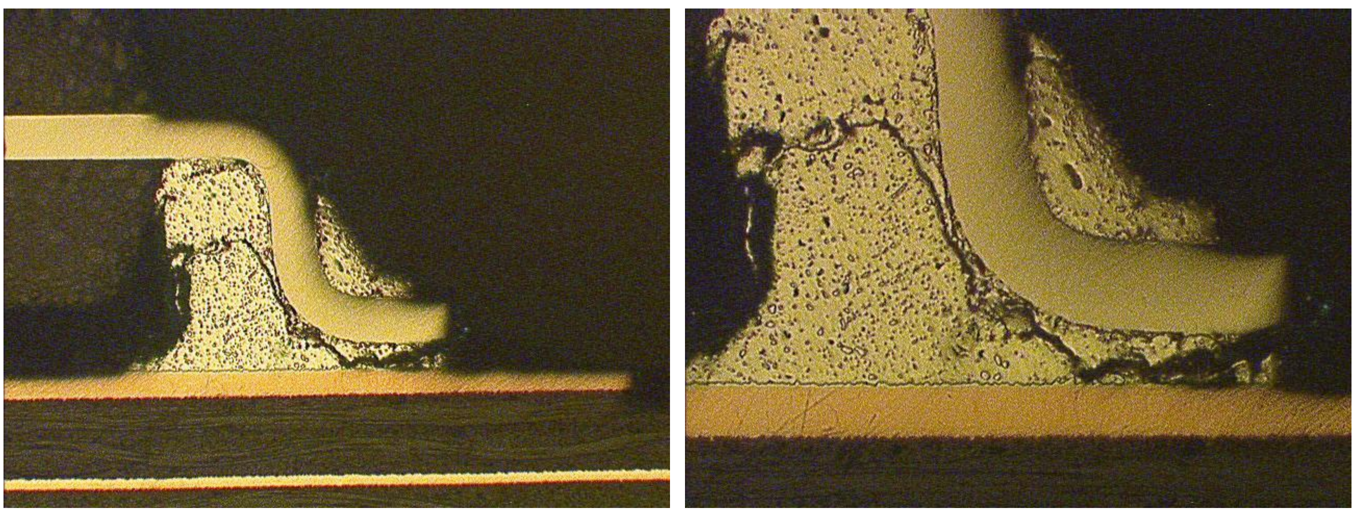


Figure 67: TSOP-50 Solder Joints, Board 44, Component U25, SAC305/SnPb, Failed @ 1787 Cycles

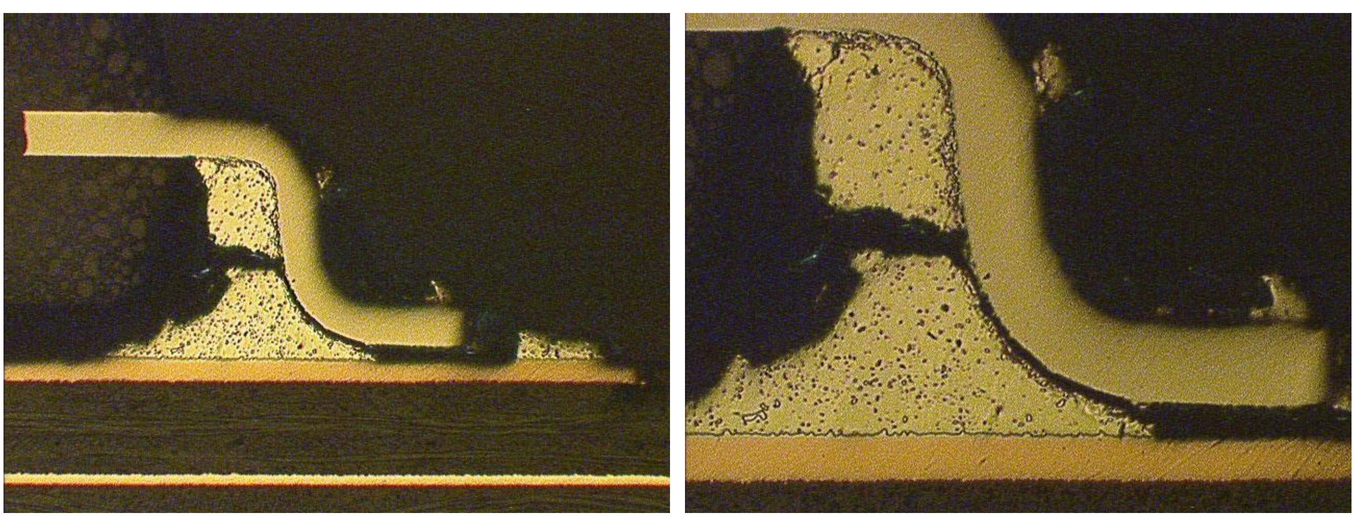


Figure 68: TSOP-50 Solder Joints, Board 103, Component U39, SN100C/SnPb, Failed @ 851 Cycles

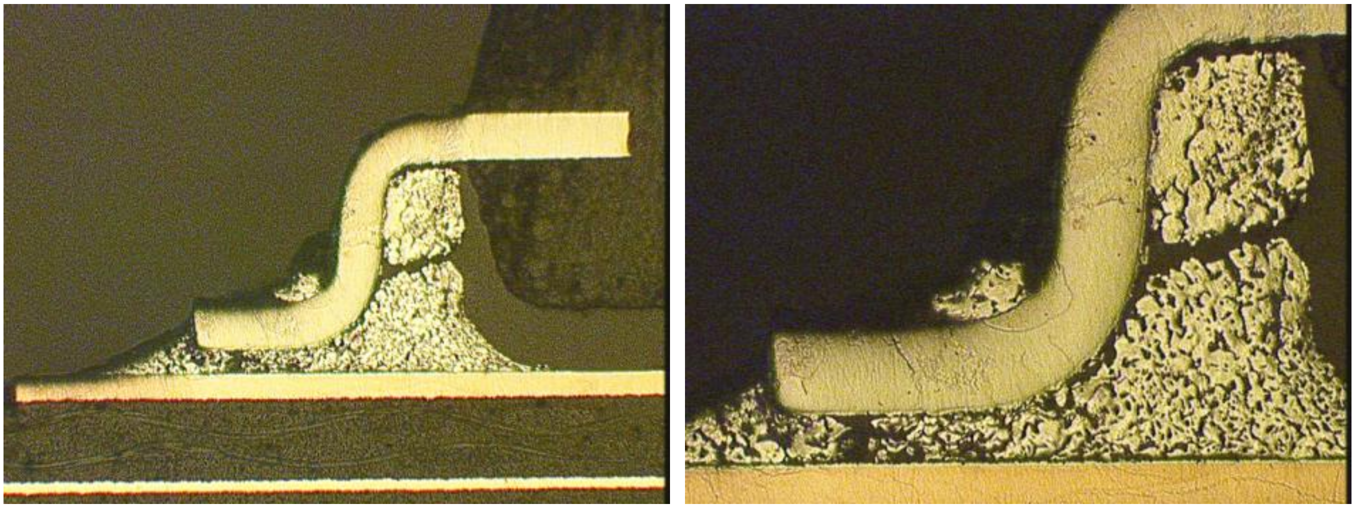


Figure 69: TSOP-50 Solder Joints, Board 8, Component U29, SnPb/SnBi, Failed @ 1424 Cycles

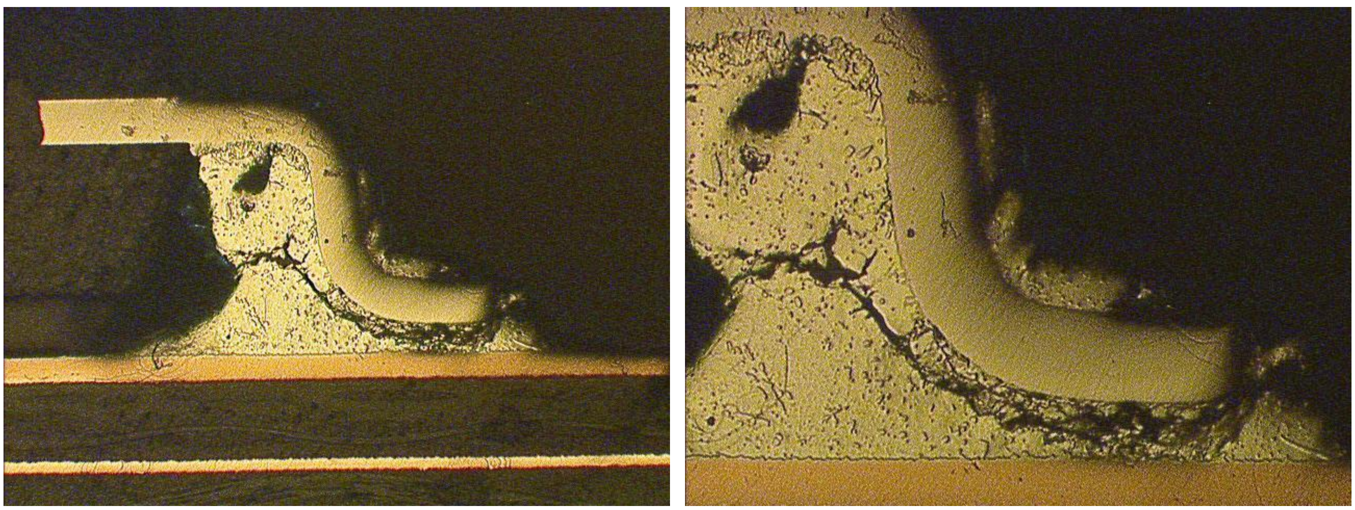


Figure 70: TSOP-50 Solder Joints, Board 166, Component U39, SAC305/SnBi, Failed @ 1594 Cycles

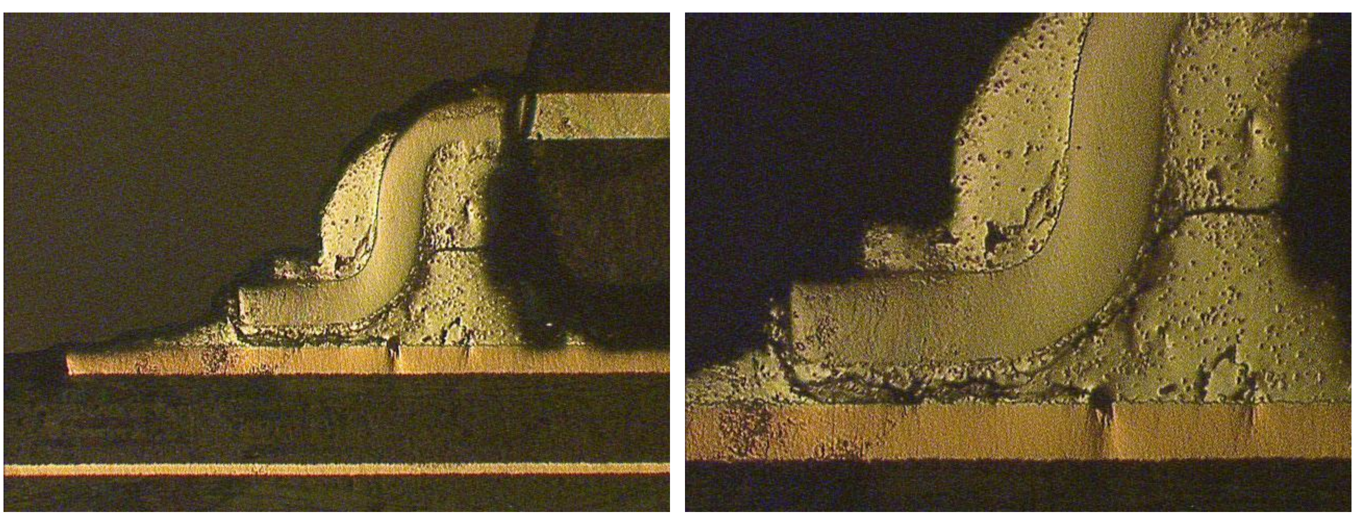


Figure 71: TSOP-50 Solder Joints, Board 102, Component U34, SN100C/SnBi, Failed @ 1985 Cycles

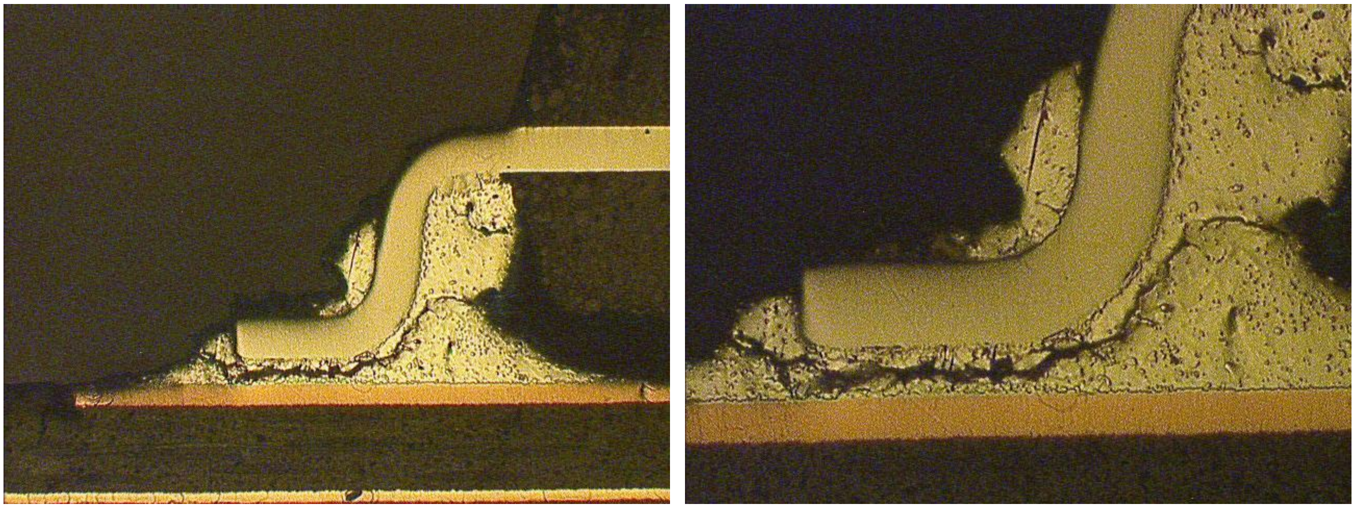


Figure 72: TSOP-50 Solder Joints, Board 107, Component U61, SN100C/Sn, Failed @ 1258 Cycles

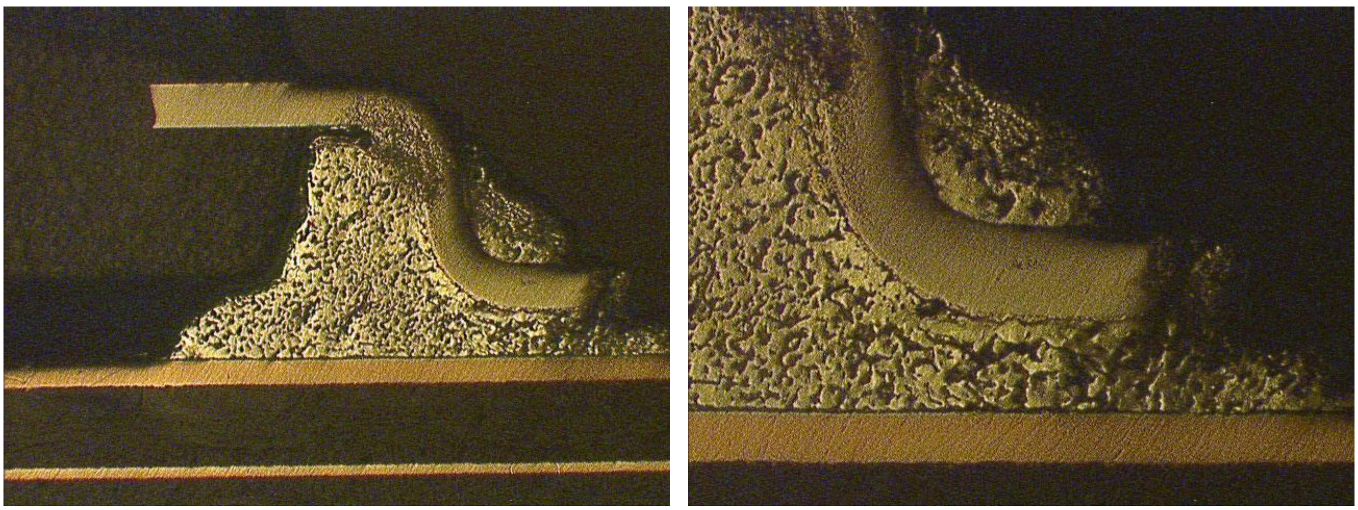


Figure 73: Reworked TSOP-50 Solder Joints, Board 127, Component U12, Initially SnPb/SnPb, 1 rework SnPb/SnPb, Failed @ 1443 Cycles

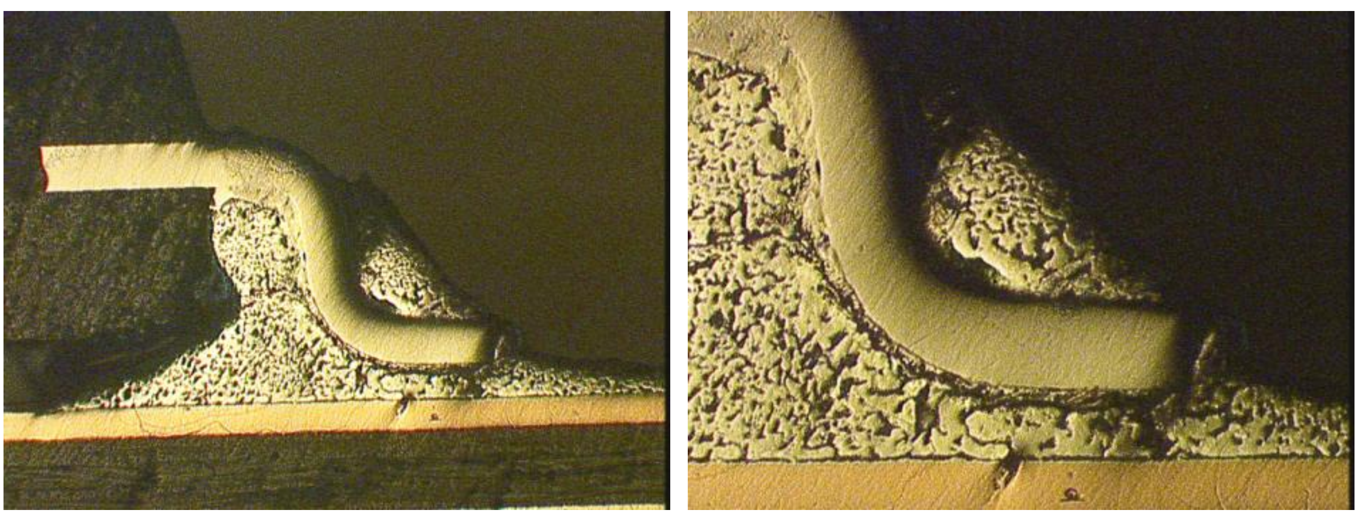


Figure 74: Reworked TSOP-50 Solder Joints, Board 47, Component U24, Initially SAC305/SnBi, 2 rework SnPb/SnBi, Failed @ 1810 Cycles

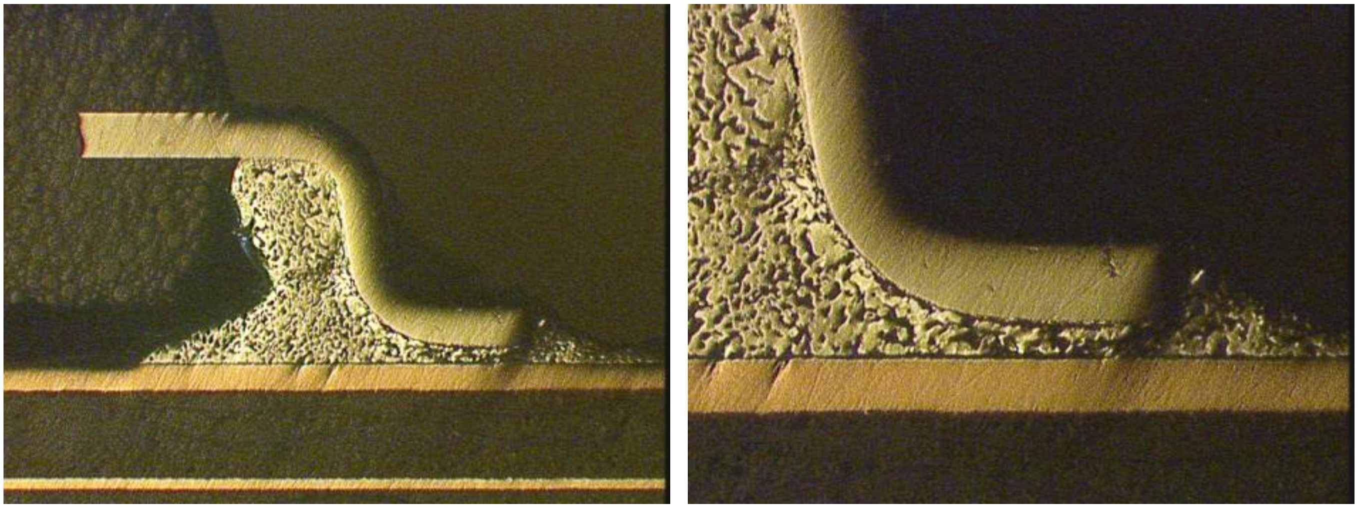


Figure 75: Reworked TSOP-50 Solder Joints, Board 47, Component U29, Initially SAC305/Sn, 1 rework SnPb/Sn, Failed @ 1010 Cycles

Dual In-Line Package (PDIP-20) Results

Statistical Analysis

The PDIP-20 components had accumulated 38% population failure after the completion of 4068 thermal cycles. The solder joint failure behavior of the PDIP-20 components was a surprise to the consortium team as the PDIP-20 failure rate documented in the JCAA/JGPP investigation results was only <u>8%</u> after 4743 total thermal cycles. Physical failure analysis of the failed PDIP-20 components revealed a test vehicle fabrication error as the root cause of the dramatically different failure rates. In-depth statistical analyses of test vehicles that contained and did not contain the fabrication defect reveal a significant difference in the results (see Table 5). Plotting of the PDIP-20 components by assembly lot designation conducted by Aaron Pedigo, NSWC Crane, is shown in Figure 76 and Figure 77. The plotted data is in agreement with Table 5 data and illustrates how assembly lots F, G, and I were compromised by the fabrication defect

PDIP-20 Test Combination			**Test vehicles with fab defect**			**Test vehicles without fab defect**		
board finish	***solder***	***component finish***	***# samples***	***failure rate***	***first failure***	***# samples***	***failure rate***	***first failure***
Immersion Ag	SAC305	NiPdAu	0	n/a	n/a	5	20%	1322
		Sn	0	n/a	n/a	5	20%	1593
	SN100C	NiPdAu	17	65%	1037	6	24%	1565
		Sn	46	96%	1024	36	8%	2454
	SnPb	NiPdAu	3	0%	n/a	32	0%	n/a
		Sn	3	100%	2858	31	55%	1010*
ENIG	SN100C	NiPdAu	7	43%	2090	0	n/a	n/a
		Sn	1	100%	2044	0	n/a	n/a
	SnPb	NiPdAu	0	n/a	n/a	3	0%	n/a
		Sn	0	n/a	n/a	3	0%	n/a

Table 5: Comparison of Test Vehicles With and Without Fabrication Defect: *Note - one failure at 1 cycle excluded from data analysis

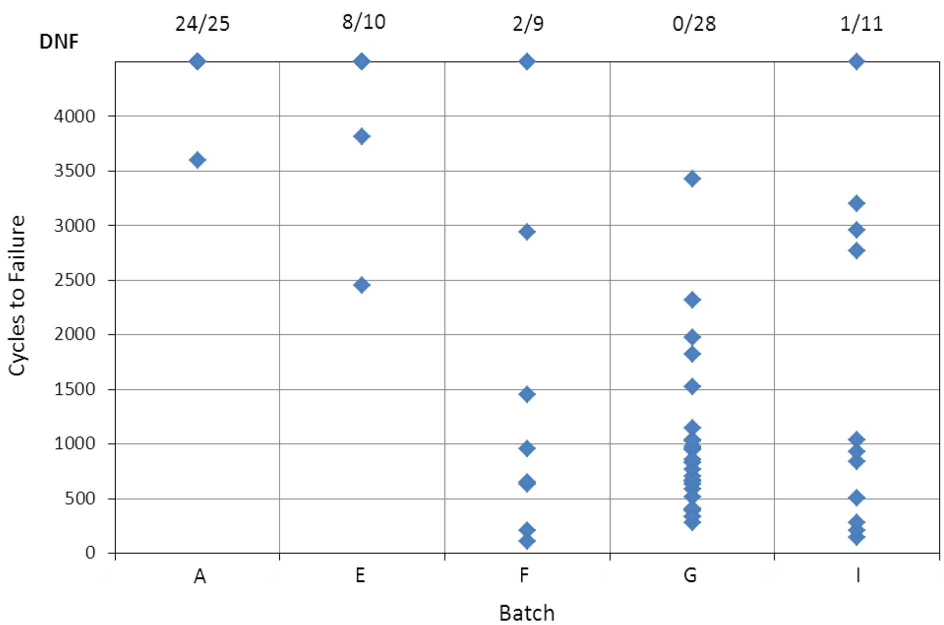


Figure 76: Cycles to failure for as-manufactured Sn finished PDIP's soldered with SN100C as a function of production batch showing a faster rate of failure for batches F, G, and I.

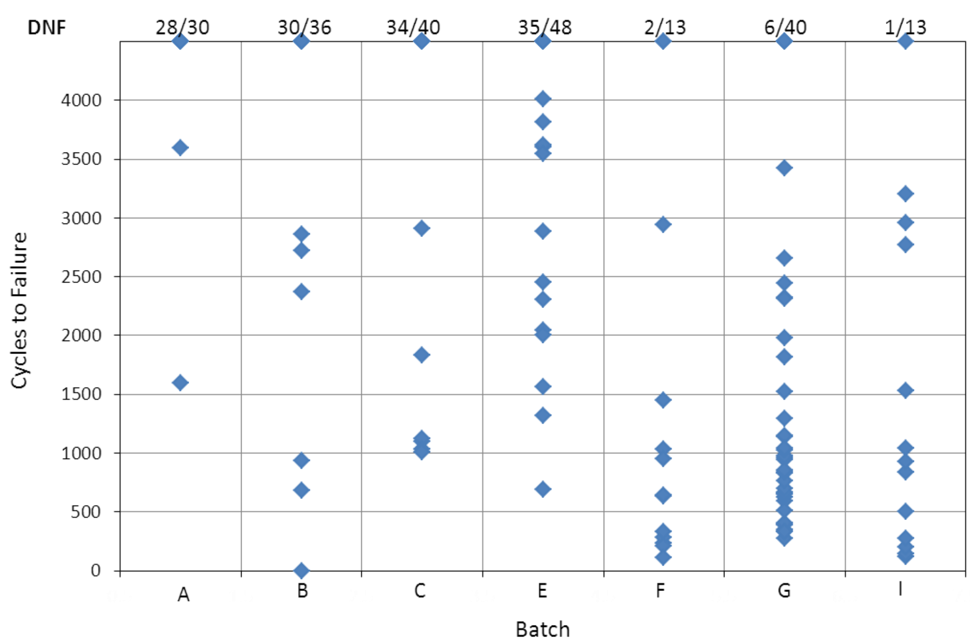
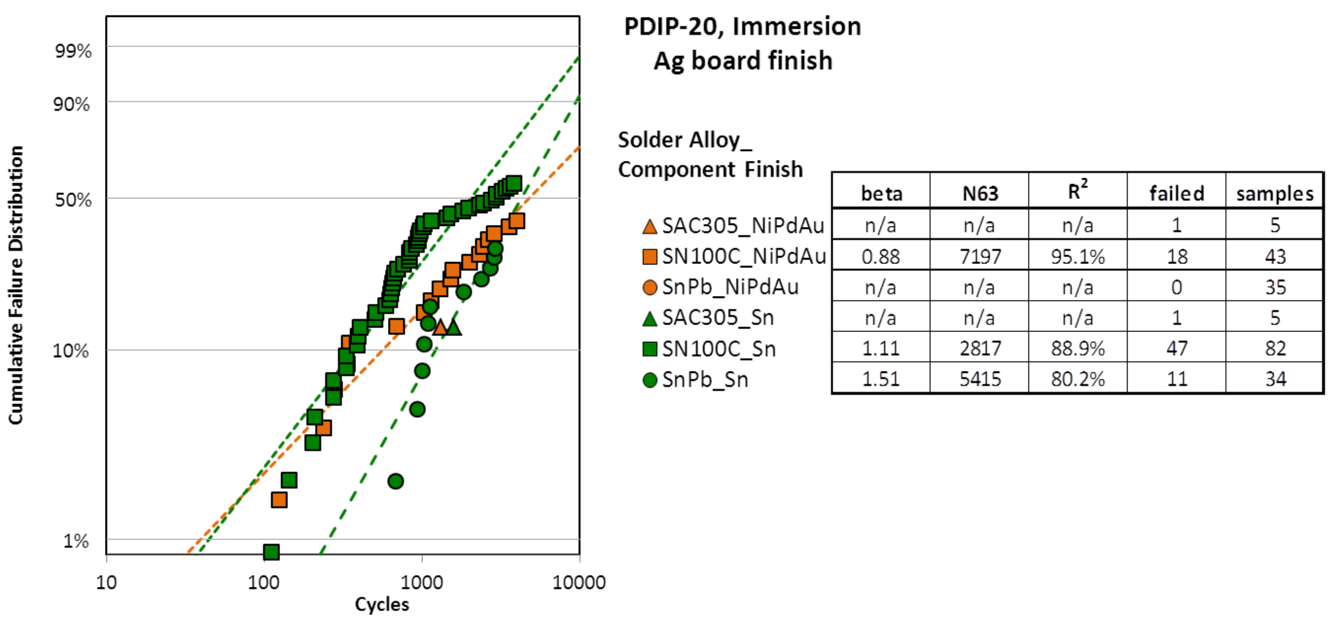


Figure 77: Cycles to failure agglomerated for all as-manufactured PDIP's as a function of production batch showing a faster rate of failure for batches F, G, and I.

The fabrication defect, which will be thoroughly described in the next section, was found on all of the test vehicles. However, post test electrical continuity testing showed that the defect only influenced the results for the PDIP-20 components, which were the only Plated Through Hole (PTH) components in the test. It is believed that the thermal expansion of the PDIP-20 leads within the plated through holes generated z-axis stress that cracked the traces at the defect. The other surface mount components did not produce these out-of-plane stresses and therefore did not encounter these same false failures due to broken circuit traces at the defect. PDIP-20 components had six different combinations (SN100C/Sn, SN100C/NiPdAu, SnPb/NiPdAu, SnPb/Sn, SAC305/NiPdAu, SAC305/Sn) tested. The SN100C/NiPdAu and SnPb/Sn combinations had similar thermal cycle performance results that were slightly better than the other combinations. The remaining combinations – SAC305/NiPdAu, SnPb/NiPdAu, and SAC305/Sn – had insufficient failures to produce valid Weibull characteristics. The number of solder joint failures for the ENIG test vehicles was very small and therefore no conclusions were made.

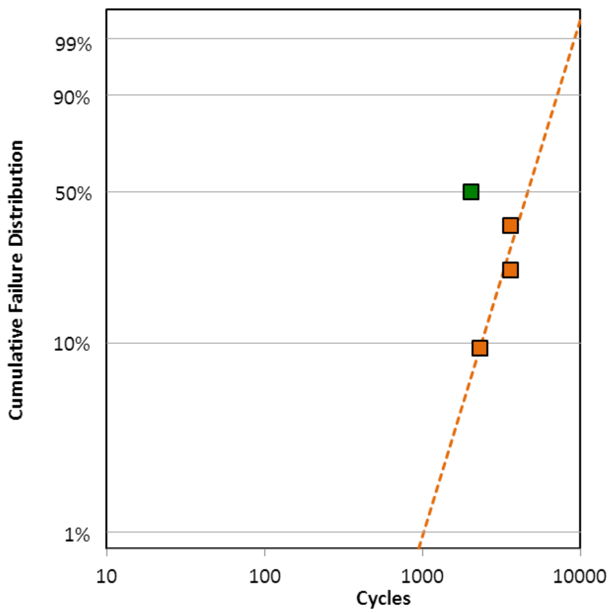
The reworked PDIP-20 components had accumulated 56% population failure after the completion of 4068 thermal cycles. The non-mixed metallurgy alloy/component finish combinations exhibited better thermal cycle performances than mixed metallurgy combination. The reworked PDIP-20 components with mixed metallurgy combinations showed the same thermal cycle results trends as the mixed metallurgy PBGA-225 alloy/component finish combinations despite being two completely different component technologies (Plated Through Hole versus Surface Mount), demonstrating that a mixed metallurgy situations tend to have more degraded solder joint integrity.

The Weibull plots in Figure 78 through Figure 80 summarize the TSOP-50 thermal cycle test results.



	beta	N63	R^2	failed	samples
SAC305_NiPdAu	n/a	n/a	n/a	1	5
SN100C_NiPdAu	0.88	7197	95.1%	18	43
SnPb_NiPdAu	n/a	n/a	n/a	0	35
SAC305_Sn	n/a	n/a	n/a	1	5
SN100C_Sn	1.11	2817	88.9%	47	82
SnPb_Sn	1.51	5415	80.2%	11	34

Figure 78: PDIP-20 Weibull Plot for Immersion Silver PWB Finish

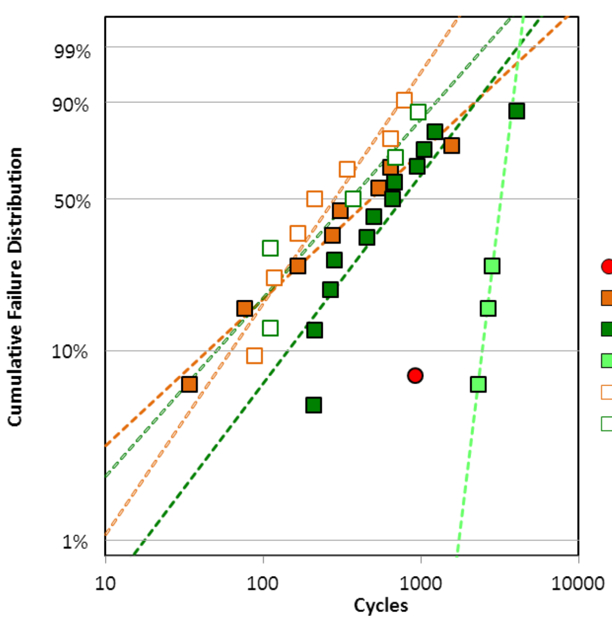


PDIP-20, ENIG board finish

Solder Alloy_ Component Finish

	beta	N63	R^2	failed	samples
SN100C_NiPdAu	2.79	5292	87.7%	3	7
SnPb_NiPdAu	n/a	n/a	n/a	0	3
SN100C_Sn	n/a	n/a	n/a	1	1
SnPb_Sn	n/a	n/a	n/a	0	3

Figure 79: PDIP-20 Weibull Plot for ENIG PWB Finish



PDIP-20, Immersion Ag board finish, reworked

Solder Alloy_ Component Finish_ # of reworks-rwk solder

	beta	N63	R^2	failed	samples
SnPb_SnPb_1-SnPb	n/a	n/a	n/a	1	9
SN100C_NiPdAu_1-SnPb	0.79	760	97.0%	8	10
SN100C_Sn_ 1-SnPb	1.12	1065	81.2%	12	13
SN100C_Sn_1-SN100C	6.93	3390	99.8%	3	10
SN100C_NiPdAu_ 2-SnPb	1.25	378	92.4%	7	7
SN100C_Sn_2-SnPb	0.96	523	87.5%	5	5

Note: 2 parts SnPb_SnPb:_ 1-SnPb on ENIG did not fail

Figure 80: Reworked PDIP-20 Weibull Plot

Physical Failure Analysis

Metallographic cross-sectional analysis was conducted on the PDIP-20 components to document the solder joint failure location, crack morphology and solder joint microstructure. One of the issues observed during the NASA DoD testing program was the significant solder joint integrity difference in the PDIP-20 components in comparison with the JCCA/JGGP testing program results. Failure analysis reviewed a fabrication defect in the test vehicle associated with the surface traces for the PDIP-20 components. Poor cleaning/entrapment of fabrication chemistry resulted in the removal of copper beneath the soldermask. Figure 81 and Figure 82 shows a cross-sectional view of the fabrication defect in the test vehicle at the PDIP-20 locations. Fabrication chemistry was trapped under the soldermask edge along the PDIP-20 pads resulting in a reduction of the copper trace thickness.

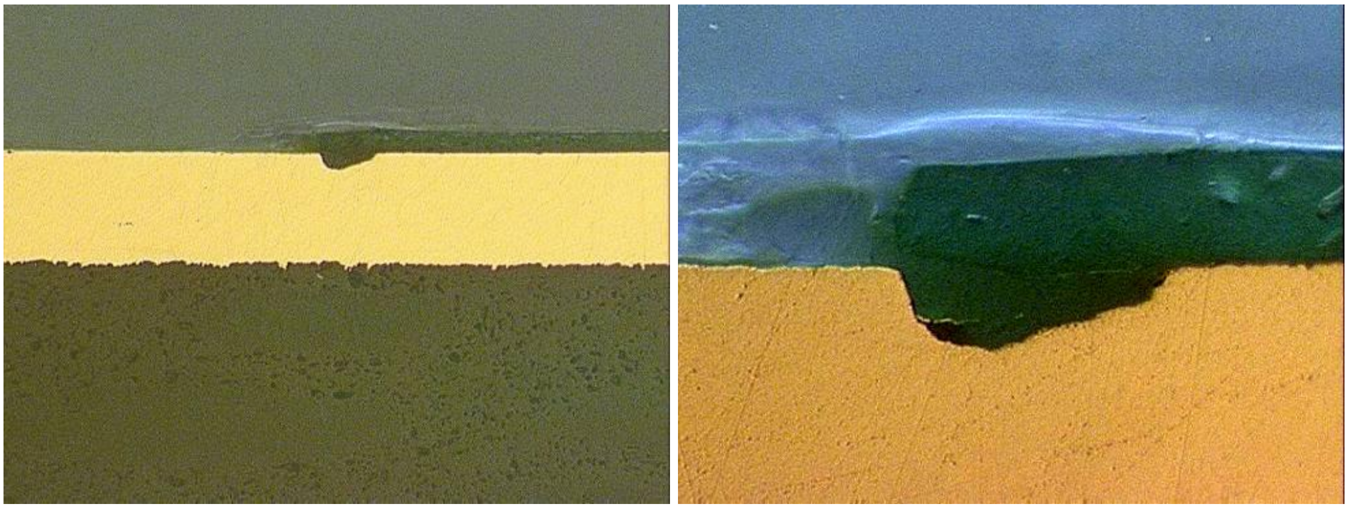


Figure 81: Cross-sectional Views of the Fabrication Defect in the Test Vehicle at the PDIP-20 Locations (Left – Macro View, Right – Magnified View)

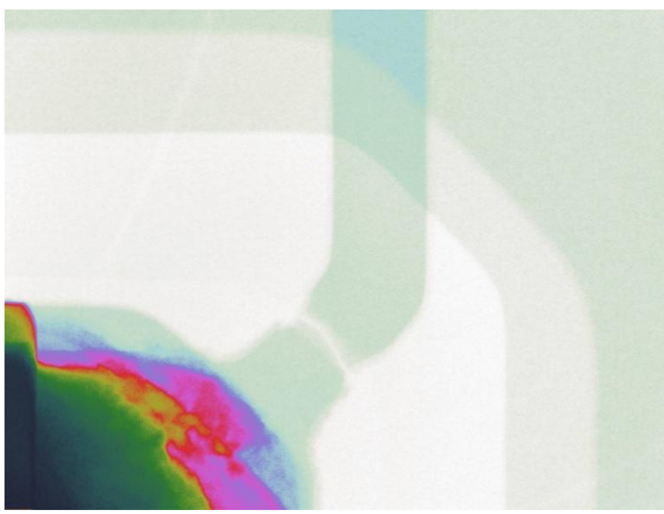


Figure 82: Color X-ray Image of PDIP-20 Thermal Cycling Induced Cracked Trace

This "necked down" region of the trace cracked during thermal cycling. In addition, the lead-free solder alloys had additional trace integrity degradation due to their copper dissolution characteristics. Figure 83 illustrates the resulting trace cracks due to thermal cycle testing of a PDIP-20 component.

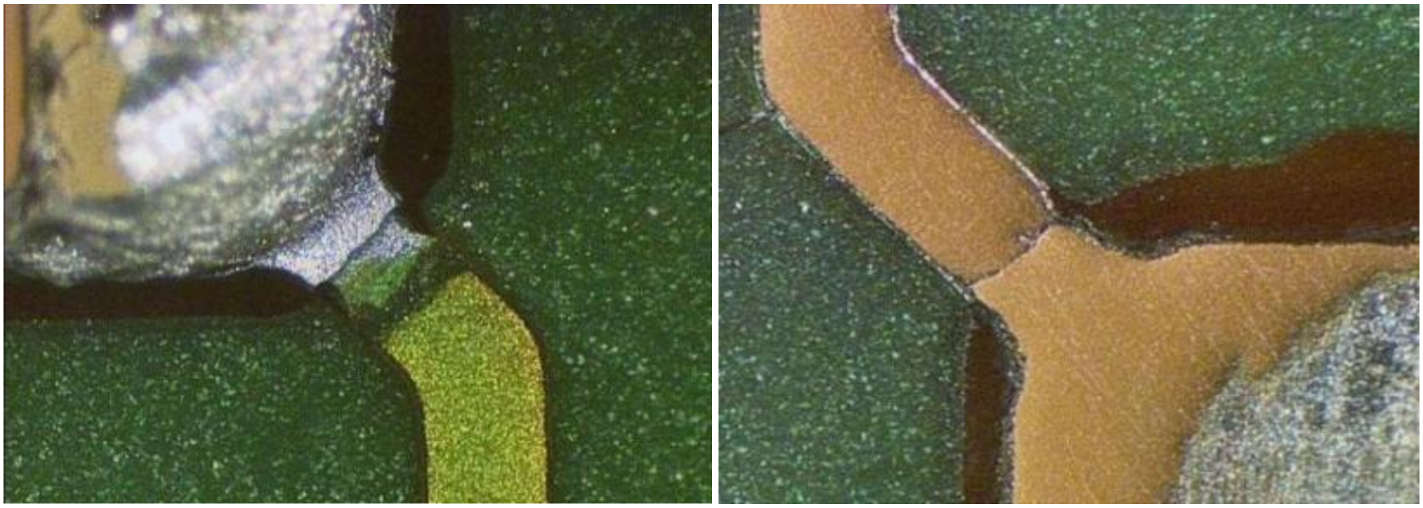


Figure 83: PDIP-20 Thermal Cycling Induced Cracked Trace at Fabrication Defect Location

Other general physical failure observations of the failed PDIP-20 components in addition to the test vehicle fabrication issue were:

- The cracks in the solder joints initiated near the plated through hole knee and traversed in the solder between the PDIP lead and plated through hole copper plating. The crack formation and location are in agreement with industry knowledge of PDIP failure modes [11].
- The solder joint geometries and wetting angles were acceptable and met industry workmanship criteria.
- The solder joint microstructures were reasonably homogenous with no segregation regions observed in the mixed metallurgy cases.

Figure 84 thru Figure 86 illustrate the typical PDIP-20 solder joint failures.

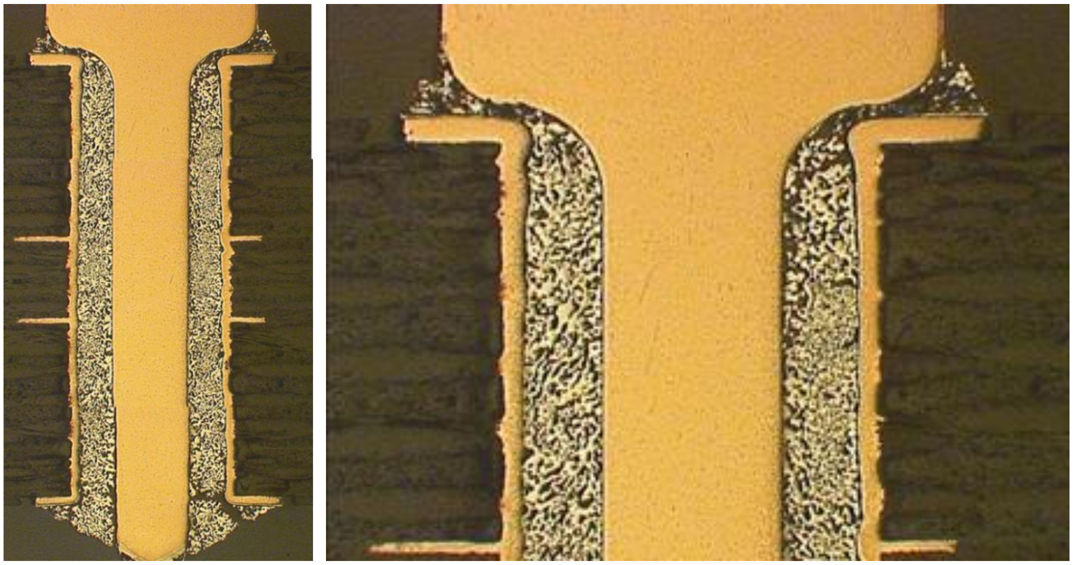


Figure 84: PDIP-20 Solder Joints, Board 124, Component U23, SnPb/NiPdAu, DNF

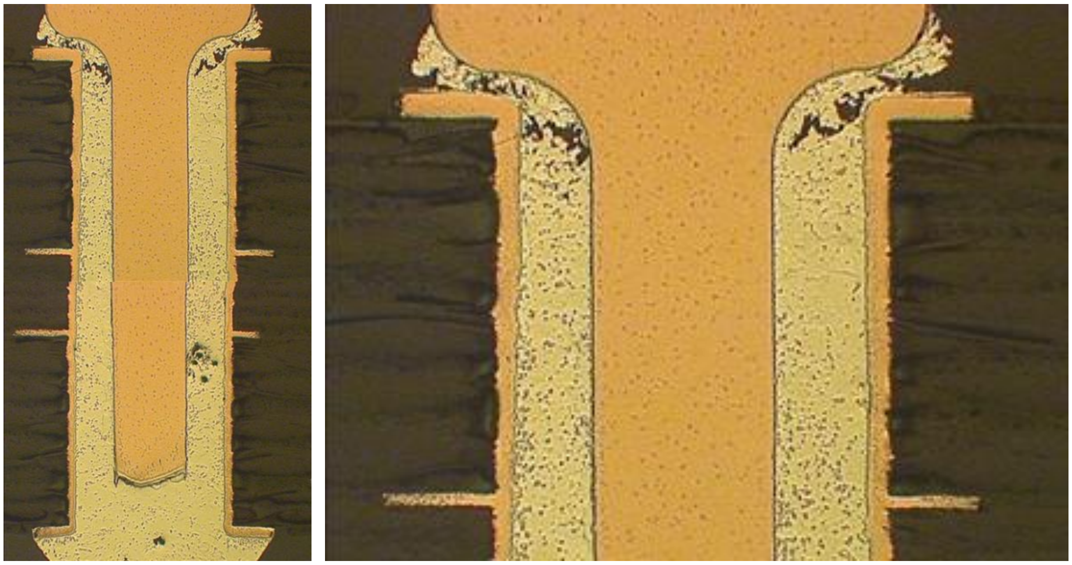


Figure 85: PDIP-20 Solder Joints, Board 43, Component U8, SN100C/NiPdAu, DNF

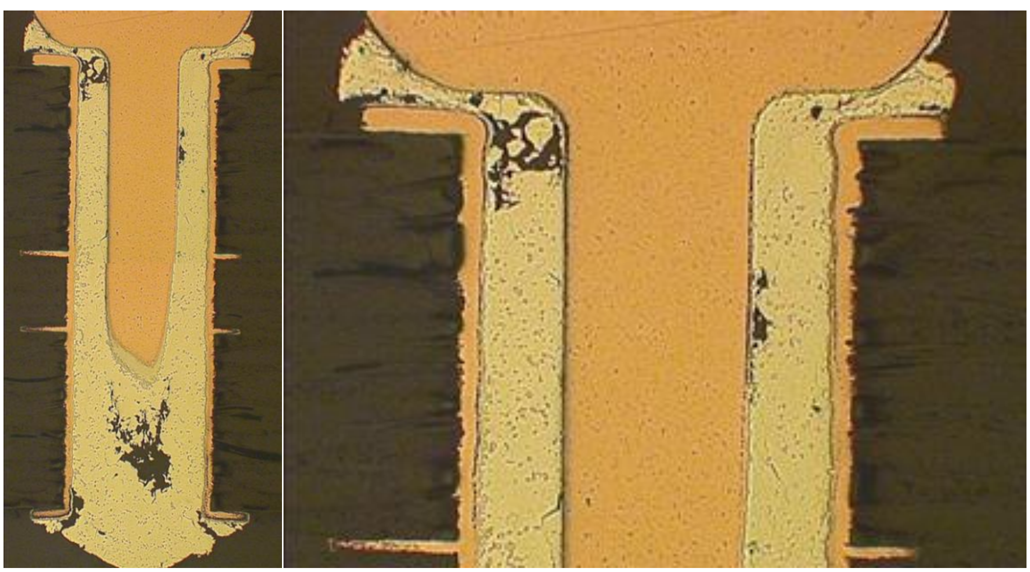


Figure 86: PDIP-20 Solder Joints, Board 168, Component U49, SN100C/Sn, DNF

Tin Whisker Inspection of Pure Tin Surfaced Finished Components

The test vehicles were inspected for the presence of tin whiskers on the three components: TQFP-144, PDIP-20, TSOP-50. These components had a pure tin surface finish as one of the possible surface finish test variables and had lead dimensions high enough to insure that poisoning by the tin/lead soldering process would not be achieved. Visual inspection was conducted using the NASA Goddard protocol [12] on the entire test vehicle population. No tin whiskers were observed during these inspections. A number of the TSOP-50 components were removed from the test vehicles for examination using scanning electron microscopy (SEM). This analysis was conducted during the JCAA/JGPP program which resulted in tin whisker observations. Figure 87 illustrates the tin whisker observed on a TSOP-50 component from the JCAA/JGPP program analysis [1].

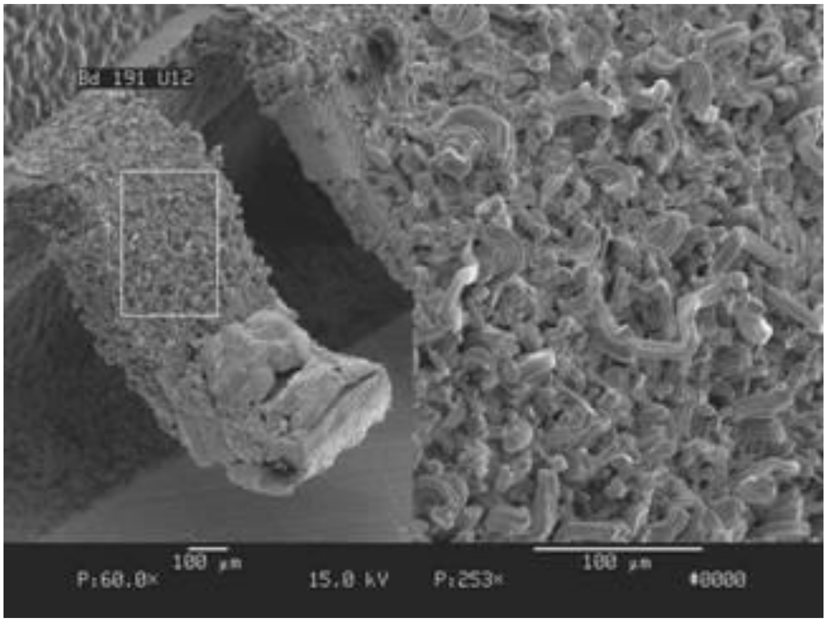


Figure 87: SEM image of TSOP component with SnCu surface finish showing tin whiskers on lead face [1]

Tin whiskers were observed on the TSOP-50 components during the SEM examination on the NASA DoD test vehicles. These tin whiskers were typically less than 20 um in length and severely contorted. The contorted shape and exposure to 4068 thermal cycles made their identification under optical microscopy examination impossible. No instances of the tin whiskers violating minimum electrical spacing requirements were documented and the authors concluded these tin whiskers would have zero impact on the function of a production assembly utilizing conformal coating.

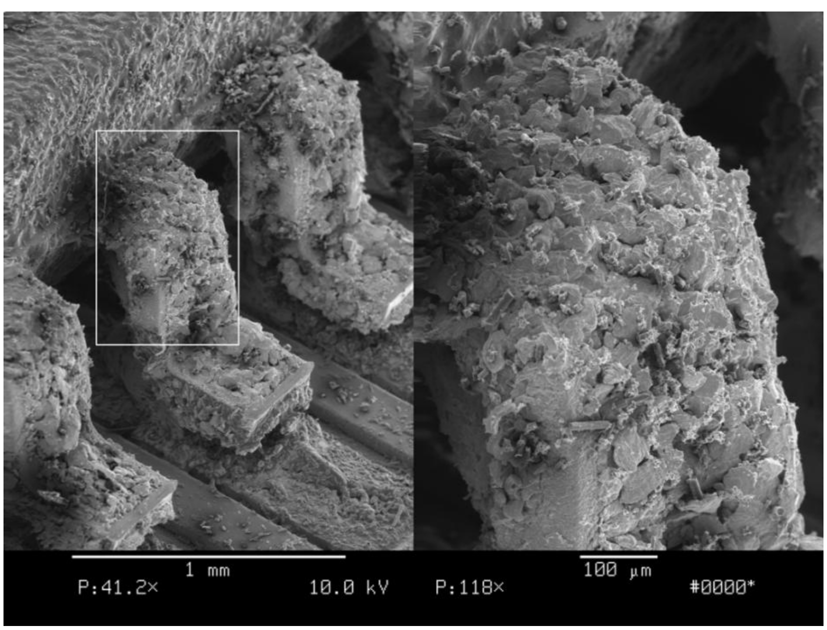


Figure 88: Tin Whiskers Observed on TSOP-50 Component after 4068 Thermal Cycles

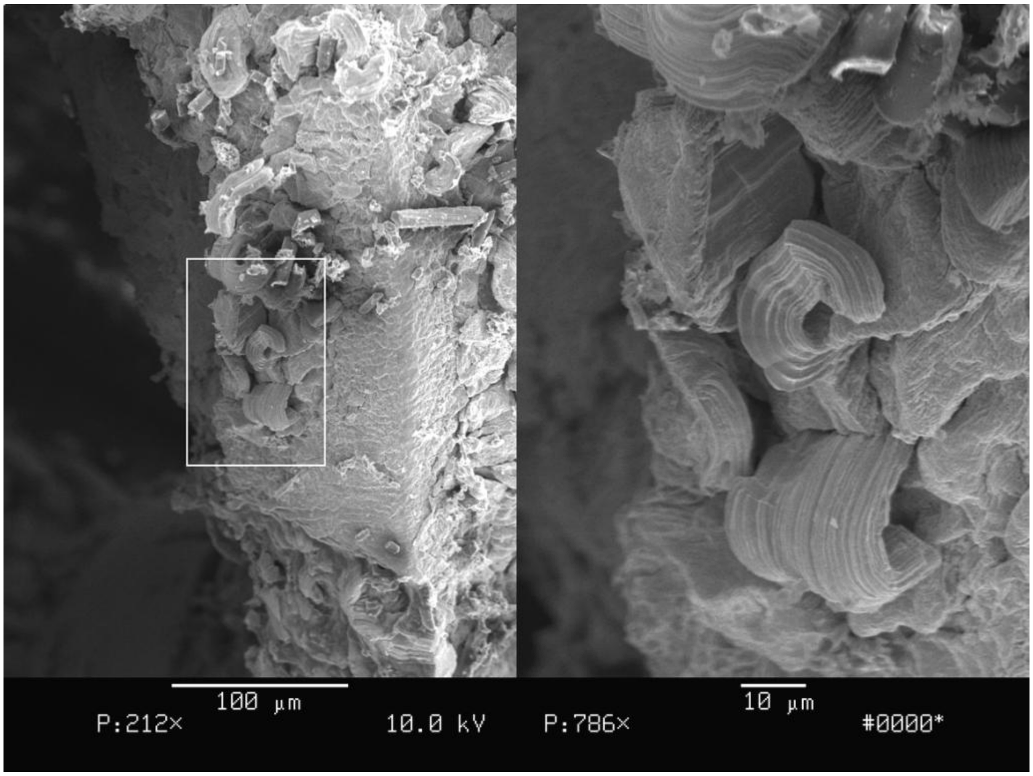


Figure 89: Typical Tin Whiskers Observed on TSOP-50 Sn Finished Component after 4068 Thermal Cycles

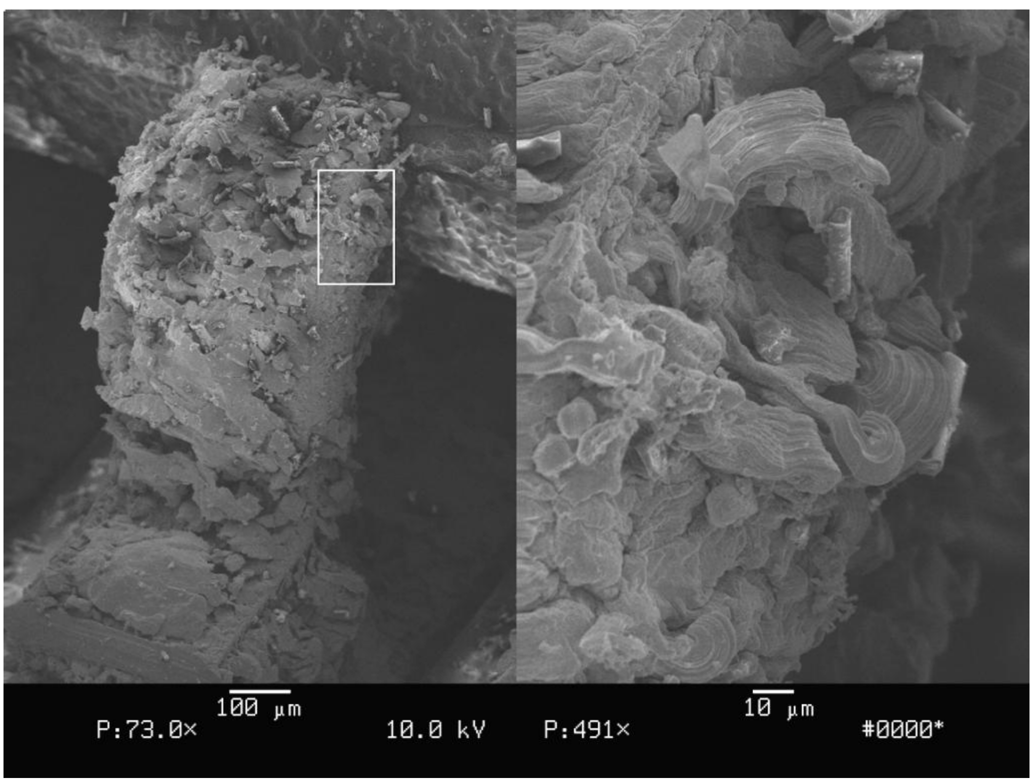


Figure 90: Additional Tin Whiskers Observed on TSOP-50 Sn Finished Component after 4068 Thermal Cycles

DISCUSSION

The main "take aways" from the thermal cycle testing project are:

- The CLCC-20 and the TSOP-50 components functioned as designed within the DOE matrix. Both component types have known failure issues in High Performance electronic products and both are considered "high stress" solder joint integrity situations. The investigation test data shows that the SnPb outperformed both Lead-free solder alloys in agreement with the JCAA/JGPP program results [1] and conventional industry published data [3].

- The rework portion of the DOE matrix was severely scrutinized prior to execution in an effort to minimize test result variation due to the rework processes/procedures. The "flux only" procedures which are widely used industry area array rework/repair procedures were problematic for the lead-free BGA and CSP DOE parameter segments. The poor performance of several of the rework/repair alloy/component finish combinations may be a maturity issue or a process refinement issue but it is clear that additional rework trials and process refinement are necessary in this area of lead-free solder processes.

- The physical failure analysis of the CSP-100 components revealed severe solder joint deformation. The SnPb solder alloy joints had readily apparent regions of grain coarsening and the Lead-free solder alloys had significant "spider web cracking" and joint deformation – both indications that the use of CSP-100 components in high performance electronic products, regardless of solder alloy selection, needs to be conducted with due diligence.

- The PDIP-20 thermal cycle results were confounded by the test vehicle fabrication error. This is an unfortunate portion of the test program but demonstrates that components with industry established solder joint integrity reputations can fall victim to other failure mechanisms. A detailed analysis of the PDIP-20 components thermal cycle performance with verse without the fabrication defect and comparison to published industry data [11] reveals that the solder joint integrity performance would be similar to the JCAA/JGPP test program results when the test vehicle fabrication confounded components are eliminated. The NASA DoD 38% PDIP failure rate is more of a measure of the fabrication error than an increase of the JCAA/JGPP 8% PDIP failure rate.

- The QFN-20 component was a new component style for the consortium as it was not included in the JCAA/JGPP test program. The QFN-20 component had the best overall thermal cycle solder joint integrity of all the component styles tested. The results demonstrate that the QFN style component can find application in a number of High Performance electronic product use environments. It should be noted that the QFN-20 components used in the thermal cycle testing contained a metallized thermal pad that was soldered to the test vehicles that has a significant influence on the thermal cycle solder joint integrity in comparison to QFN components without metallized thermal pads.

- There were no surprises in the PBGA-225 thermal cycle test results. The test results demonstrated that mixed metallurgy situations are non-optimal. An all SnPb or all Lead-free solder alloy/component finish combination had a more consistent, predictable final solder joint integrity result compared to a mixed alloy solder joint configuration. The impact of mixed metallurgy solder joints and the influence of reflow profiles on producing uniform solder joint microstructures has been shown in other industry investigations [8].

ACKNOWLEDGEMENTS

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Appendix A N1/N10/N63 Solder Performance for -55C to +125 C Thermal Cycle Testing

Solder Performance				
Component	**Solder/Finish**	**1st Failure**	**N10**	**N63**
BGA-225	SnPb/SnPb	2041 (25 samples)	2089	2536
	SnPb/SAC405	443 (44 samples)	1027	4649
	SAC305/SnPb	166 (45 samples)	644	2132
	SAC305/SAC405	2509 (65 samples)	2706	3367
	SN100C/SnPb	216 (25 samples)	286	1393
	SN100C/SAC405	308 (65 samples)	1849	4982
	SAC305/SnPb (ENIG)	111 (5 samples)	NF	4086
	SAC305/SAC405 (ENIG)	2819 (5 samples)	NF	4291
	SnPb/SAC405 (ENIG)	3676 (4 samples)	NF	NF
CSP-100	SnPb/SnPb	2248 (25 samples)	2404	2913
	SnPb/SAC105	287 (44 samples)	2692	70225
	SAC305/SnPb	355 (40 samples)	1433	4041
	SAC305/SAC105	626 (69 samples)	2501	6108
	SN100C/SnPb	851 (24 samples)	1680	3409
	SN100C/SAC105	2769 (25 samples)	3045	3721
	SAC305/SnPb (ENIG)	2123 (5 samples)	1930	2731
	SAC305/SAC105 (ENIG)	3661 (5 samples)	NF	NF
	SnPb/SAC105 (ENIG)	280 (4 samples)	NF	NF
CLCC-20	SnPb/SnPb	482 (20 samples)	536	1954
	SnPb/SAC305	341 (75 samples)	320	1060
	SAC305/SnPb	124 (70 samples)	256	1148
	SAC305/SAC305	315 (47 samples)	319	952
	SN100C/SnPb	369 (25 samples)	244	1014
	SN100C/SAC305	304 (48 samples)	320	1015
	SAC305/SnPb (ENIG)	501 (5 samples)	250	1468
	SAC305/SAC305 (ENIG)	426 (5 samples)	262	836
	SnPb/SAC305 (ENIG)	390 (10 samples)	229	805
PDIP-20	SnPb/SnPb	NA	NA	NA
	SnPb/Sn	682 (34 samples)	1220	5415
	SnPb/NiPdAu	DNF (35 samples)	NF	NF
	SAC305/SnPb	NA	NA	NA
	SAC305/Sn	1593 (5 samples)	NF	NF
	SAC305/ NiPdAu	1322 (5 samples)	NF	NF
	SN100C/SnPb	NA	NA	NA
	SN100C/Sn	111 (82 samples)	371	2817
	SN100C/ NiPdAu	124 (43 samples)	558	7197
	SN100C/NiPdAu (ENIG)	2309 (7 samples)	NF	NF
	SnPb/NiPdAu (ENIG)	DNF (3 samples)	NF	NF
	SN100C/Sn (ENIG)	2044 (1 sample)	NF	NF
	SnPb/Sn (ENIG)	DNF (3 samples)	NF	NF

*NF = Insufficient Failures to generate Weibull N10 and N63Values

*NA = Solder Alloy/Component Finish Combination Not On Thermal Cycle Test Vehicles

Appendix B N1/N10/N63 Solder Performance for -55C to +125 C Thermal Cycle Testing

Solder Performance				
Component	**Solder/Finish**	**1st Failure**	**N10**	**N63**
QFN-20	SnPb/SnPb	NA	NA	NA
	SnPb/Sn	DNF (50 samples)	NF	NF
	SAC305/SnPb	NA	NA	NA
	SAC305/Sn	1480 (25 samples)	NF	NF
	SN100C/SnPb	NA	NA	NA
	SN100C/Sn	2671 (25 samples)	NF	NF
	SAC305/SnPb (ENIG)	1916 (25 samples)	NF	NF
	SAC305/ Sn (ENIG)	DNF (5 samples)	NF	NF
	SnPb/ Sn (ENIG)	DNF (5 samples)	NF	NF
TQFP-144	SnPb/ SnPb	1985 (44 samples)	2257	2901
	SnPb/ Sn	1322 (28 samples)	2044	3003
	SnPb/ SAC305	NA	NA	NA
	SnPb/ NiPdAu	1169 (25 samples)	1470	2333
	SAC305/ SnPb	2291 (27 samples)	2679	3582
	SAC305/ Sn	1043 (47 samples)	1146	1774
	SAC305/ SAC305	NA	NA	NA
	SAC305/ NiPdAu	351 (25 samples)	1227	4315
	SN100C/ SnPb	1676 (25 samples)	1768	2637
	SN100C/ Sn	826 (47 samples)	1225	1756
	SN100C/ SAC305	NA	NA	NA
	SN100C/ NiPdAu	NA	NA	NA
	SAC305/Sn (ENIG)	1981 (5 samples)	1772	3219
	SAC305/SnPb (ENIG)	3827 (4 samples)	NF	NF
	SnPb/SnPb (ENIG)	2226 (5 samples)	2108	2531
	SnPb/NiPdAu (ENIG)	1307 (5 samples)	1138	2057
TSOP-50	SnPb/SnPb	1060 (19 samples)	1136	1519
	SnPb/Sn	1141 (15 samples)	1130	1415
	SnPb/SnBi	343 (38 samples)	853	1516
	SAC305/SnPb	884 (34 samples)	1031	1519
	SAC305/Sn	828 (7 samples)	724	1321
	SAC305/SnBi	789 (47 samples)	891	1298
	SN100C/SnPb	863 (25 samples)	917	1424
	SN100C/Sn	755 (8 samples)	765	1123
	SN100C/SnBi	790 (32 samples)	848	1191
	SAC305/SnPb (ENIG)	281 (5 samples)	248	1916
	SnPb/Sn (ENIG)	1097 (3 samples)	NF	NF
	SAC305/SnBi (ENIG)	1141 (5 samples)	1118	1461

*NF = Insufficient Failures to generate Weibull N10 and N63Values

*NA = Solder Alloy/Component Finish Combination Not On Thermal Cycle Test Vehicles

Appendix C N1/N10/N63 Solder Rework Performance for -55C to +125 C Thermal Cycle Testing

"NF" Solder Performance				
Component	**Solder/Finish/Rework**	**1st Failure**	**N10**	**N63**
BGA-225	SnPb/SnPb/SnPb	813 (15 samples)	853	2737
	SAC305/SAC405/SnPb	2138 (15 samples)	NF	7237
	SnPb/SnPb/Flux Only	2144 (10 samples)	2110	2512
	SAC305/SAC405/Flux Only	983 (15 samples)	1710	4118
	SnPb/SAC405/Flux Only	1907 (5 samples)	1779	2604
	SnPb/SnPb/SnPb (ENIG)	DNF (3 samples)	NF	NF
	SnPb/SnPb/Flux Only (ENIG)	1760 (2 samples)	NF	NF
	SnPb/SAC405/Flux Only (ENIG)	1794 (1 samples)	NF	NF
CSP-100	SnPb/SnPb/SnPb	DNF (15 samples)	NF	NF
	SAC305/SAC105/SnPb	DNF (15 samples)	NF	NF
	SAC305/SAC105/SAC305	3795 (1 samples)	NF	NF
	SnPb/SnPb/Flux Only	2550 (15 samples)	2568	3059
	SAC305/SAC105/Flux Only	3458 (12 samples)	NF	NF
	SAC305/SAC105/Flux Only (2)	2299 (3 samples)	NF	2858
	SnPb/SnPb/1-SnPb	3488 (3 samples)	NF	NF
	SnPb/SnPb/Flux Only	1525 (3 samples)	NF	2020
PDIP-20	SnPb/SnPb/SnPb	928 (9 samples)	NF	NF
	SN100C/NiPdAu/SnPb	34 (10 samples)	44	760
	SN100C/Sn/SnPb	209 (13 samples)	143	1065
	SN100C/Sn/SN100C	2304 (10 samples)	NF	3390
	SN100C/NiPdAu/ SnPb (2)	88 (7 samples)	62	378
	SN100C/Sn/SnPb (2)	111 (5 samples)	50	523
TSOP-50	SnPb/SnPb/SnPb	272 (20 samples)	673	1739
	SAC305/Sn/SnPb	824 (16 samples)	979	1670
	SN100C/Sn/SnPb	1058 (6 samples)	1007	1470
	SAC305/SnBi/SnPb	801 (6 samples)	716	1294
	SN100C/SnBi/SnPb	801 (6 samples)	714	1395
	SAC305/SnPb/SAC305	765 (4 samples)	NF	1348
	SAC305/SnBi/SAC305	879 (10 samples)	921	1265
	SAC305/Sn/ SnPb (2)	963 (7 samples)	930	1333
	SN100C/Sn/ SnPb (2)	963 (6 samples)	957	1394
	SAC305/SnBi/ SnPb (2)	933 (7 samples)	1001	1656
	SN100C/SnBi/ SnPb (2)	326 (7 samples)	398	1496
	SnPb/SnPb/SnPb (ENIG)	336 (4 samples)	NF	1709
QFN	SAC305/Sn/SnPb	DNF (7 samples)	NF	NF
	SN100C/Sn/ SnPb	277 (6 samples)	NF	NF
	SAC305/Sn/SnPb (2)	DNF (6 samples)	NF	NF
	SN100C/ Sn/ SnPb (2)	DNF (7 samples)	NF	NF
	SAC305/ Sn/StencilQuik	3660 (7 samples)	NF	NF
	SN100C/Sn/StencilQuik	3547 (7 samples)	NF	NF
CLCC	SAC305/SAC305/ SnPb	319 (12 samples)	324	1122
	SN100C/SAC305/ SnPb	545 (9 samples)	539	1120
	SAC305/SAC305/SAC305	735 (1 samples)	NF	NF
	SAC305/SAC305/ SnPb (2)	473 (9 samples)	354	1195
	SN100C/SAC305/ SnPb (2)	600 (8 samples)	411	1265

*NF = Insufficient Failures to generate Weibull N10 and N63Values

Appendix D Solder Performance Comparison for -55C to +125 C Thermal Cycle Testing

Solder Performance				
Component	**Solder/Finish**	**1st Failure**	**N10**	**N63**
BGA-225	SnPb/SnPb	0	0	0
	SnPb/SAC405	--	--	++
	SAC305/SnPb	--	--	--
	SAC305/SAC405	++	++	++
	SN100C/SnPb	--	--	--
	SN100C/SAC405	--	-	++
	SAC305/SnPb (ENIG)	--	NF	++
	SAC305/SAC405 (ENIG)	++	NF	++
	SnPb/SAC405 (ENIG)	++	NF	NF
CSP-100	SnPb/SnPb	0	0	0
	SnPb/SAC105	--	+	++
	SAC305/SnPb	--	--	++
	SAC305/SAC105	--	+	++
	SN100C/SnPb	--	--	++
	SN100C/SAC105	++	++	++
	SAC305/SnPb (ENIG)	-	-	-
	SAC305/SAC105 (ENIG)	++	NF	NF
	SnPb/SAC105 (ENIG)	--	NF	NF
CLCC-20	SnPb/SnPb	0	0	0
	SnPb/SAC305	--	--	--
	SAC305/SnPb	--	--	--
	SAC305/SAC305	--	--	--
	SN100C/SnPb	--	--	--
	SN100C/SAC305	--	--	--
	SAC305/SnPb (ENIG)	+	--	--
	SAC305/SAC305 (ENIG)	-	--	--
	SnPb/SAC305 (ENIG)	-	--	--
PDIP-20	SnPb/SnPb	NA	NA	NA
	SnPb/Sn	0	0	0
	SnPb/NiPdAu	DNF	NF	NF
	SAC305/SnPb	NA	NA	NA
	SAC305/Sn	++	NF	NF
	SAC305/ NiPdAu	++	NF	NF
	SN100C/SnPb	NA	NA	NA
	SN100C/Sn	--	--	--
	SN100C/ NiPdAu	--	--	++
	SN100C/NiPdAu (ENIG)	++	NF	NF
	SnPb/NiPdAu (ENIG)	DNF	NF	NF
	SN100C/Sn (ENIG)	++	NF	NF
	SnPb/Sn (ENIG)	DNF	NF	NF

Legend:
0 = Same as control or <5% difference
+ = 5 to 20% (green)   ++ = >20% (green)
- = -5 to -20% (yellow)   -- = >-20% (red)
NA = Not Available (not enough failures)
NT = Not Tested

Appendix E N1/N10/N63 Solder Performance for -55C to +125 C Thermal Cycle Testing

Solder Performance				
Component	**Solder/Finish**	**1st Failure**	**N10**	**N63**
QFN-20	SnPb/SnPb	NA	NA	NA
	SnPb/Sn	0	NF	NF
	SAC305/SnPb	NA	NA	NA
	SAC305/Sn	--	NF	NF
	SN100C/SnPb	NA	NA	NA
	SN100C/Sn	--	NF	NF
	SAC305/SnPb (ENIG)	--	NF	NF
	SAC305/ Sn (ENIG)	DNF	NF	NF
	SnPb/ Sn (ENIG)	DNF	NF	NF
TQFP-144	SnPb/ SnPb	0	0	0
	SnPb/ Sn	--	-	+
	SnPb/ SAC305	NA	NA	NA
	SnPb/ NiPdAu	--	--	-
	SAC305/ SnPb	+	+	++
	SAC305/ Sn	--	--	--
	SAC305/ SAC305	NA	NA	NA
	SAC305/ NiPdAu	--	--	++
	SN100C/ SnPb	-	--	-
	SN100C/ Sn	--	--	--
	SN100C/ SAC305	NA	NA	NA
	SN100C/ NiPdAu	NA	NA	NA
	SAC305/Sn (ENIG)	0	--	+
	SAC305/SnPb (ENIG)	++	NF	NF
	SnPb/SnPb (ENIG)	+	-	-
	SnPb/NiPdAu (ENIG)	--	--	--
TSOP-50	SnPb/SnPb	0	0	0
	SnPb/Sn	+	-	-
	SnPb/SnBi	--	--	0
	SAC305/SnPb	-	-	0
	SAC305/Sn	--	--	-
	SAC305/SnBi	--	--	-
	SN100C/SnPb	-	-	-
	SN100C/Sn	--	--	--
	SN100C/SnBi	--	--	--
	SAC305/SnPb (ENIG)	--	--	++
	SnPb/Sn (ENIG)	+	NF	NF
	SAC305/SnBi (ENIG)	+	0	-

Legend:
0 = Same as control or <5% difference
+ = 5 to 20% (green) ++ = >20% (green)
- = -5 to -20% (yellow) -- = >-20% (red)
NA = Not Available (not enough failures)
NT = Not Tested

Appendix F Solder Rework Performance Comparison for -55C to +125 C Thermal Cycle Testing

"NF" Solder Performance				
Component	**Solder/Finish/Rework**	**1st Failure**	**N10**	**N63**
BGA-225	SnPb/SnPb/SnPb	0	0	0
	SAC305/SAC405/SnPb	++	NF	++
	SnPb/SnPb/Flux Only	++	++	-
	SAC305/SAC405/Flux Only	++	++	++
	SnPb/SAC405/Flux Only	++	++	-
	SnPb/SnPb/SnPb (ENIG)	DNF	NF	NF
	SnPb/SnPb/Flux Only (ENIG)	++	NF	NF
	SnPb/SAC405/Flux Only (ENIG)	++	NF	NF
CSP-100	SnPb/SnPb/SnPb	DNF	NF	NF
	SAC305/SAC105/SnPb	DNF	NF	NF
	SAC305/SAC105/SAC305	-	NF	NF
	SnPb/SnPb/Flux Only	-	+	+
	SAC305/SAC105/Flux Only	-	NF	NF
	SAC305/SAC105/Flux Only (2)	-	NF	+
	SnPb/SnPb/1-SnPb	-	NF	NF
	SnPb/SnPb/Flux Only	-	NF	+
PDIP-20	SnPb/SnPb/SnPb	0	NF	NF
	SN100C/NiPdAu/SnPb	--	-	-
	SN100C/Sn/SnPb	--	-	-
	SN100C/Sn/SN100C	++	NF	-
	SN100C/NiPdAu/ SnPb (2)	--	-	-
	SN100C/Sn/SnPb (2)	--	-	-
TSOP-50	SnPb/SnPb/SnPb	0	0	0
	SAC305/Sn/SnPb	++	++	-
	SN100C/Sn/SnPb	++	++	-
	SAC305/SnBi/SnPb	++	+	--
	SN100C/SnBi/SnPb	++	+	-
	SAC305/SnPb/SAC305	++	NF	--
	SAC305/SnBi/SAC305	++	++	--
	SAC305/Sn/ SnPb (2)	++	++	--
	SN100C/Sn/ SnPb (2)	++	++	-
	SAC305/SnBi/ SnPb (2)	++	++	-
	SN100C/SnBi/ SnPb (2)	+	--	-
	SnPb/SnPb/SnPb (ENIG)	+	NF	-

Legend:
0 = Same as control or <5% difference
+ = 5 to 20%   ++ = >20%
- = -5 to -20%   -- = >-20% (red if much greater than -20%)
NA = Not Available (not enough failures)
NT = Not Tested

Appendix G Solder Rework Performance Comparison for -55C to +125 C Thermal Cycle Testing

"NF" Solder Performance				
Component	**Solder/Finish/Rework**	**1st Failure**	**N10**	**N63**
QFN	SAC305/Sn/SnPb	DNF	NF	NF
	SN100C/Sn/ SnPb	-	NF	NF
	SAC305/Sn/SnPb (2)	DNF	NF	NF
	SN100C/ Sn/ SnPb (2)	DNF	NF	NF
	SAC305/ Sn/StencilQuik	-	NF	NF
	SN100C/Sn/StencilQuik	-	NF	NF
CLCC	SAC305/SAC305/ SnPb	0	0	0
	SN100C/SAC305/ SnPb	++	++	0
	SAC305/SAC305/SAC305	++	NF	NF
	SAC305/SAC305/ SnPb (2)	++	+	+
	SN100C/SAC305/ SnPb (2)	++	++	++

Legend:
0 = Same as control or <5% difference
+ = 5 to 20%   ++ = >20%
- = -5 to -20%   -- = >-20% (red if much greater than -20%)
NA = Not Available (not enough failures)
NT = Not Tested

Appendix H Failure Data - Manufactured Components

Part Style	Board Finish	Solder_ Component Finish	Failure Data
CLCC-20	ImAg	SAC305_SnPb	124, 137, 298, 302, 318, 330, 340, 353, 355, 413, 424, 429, 454, 454, 468, 474, 489, 490, 494, 495, 513, 529, 534, 557, 559, 564, 590, 590, 590, 597, 604, 624, 625, 625, 635, 640, 641, 647, 692, 699, 711, 731, 746, 776, 786, 794, 888, 981, 1060, 1226, 1230, 1248, 1461, 1577, 1813, 2125, 2298, 2592, 3049, 3485, 3555, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF
		SN100C_SnPb	369, 370, 373, 391, 391, 418, 481, 490, 513, 513, 559, 590, 626, 649, 669, 709, 713, 754, 828, 1160, 1211, 1800, 3865, DNF, DNF
		SnPb_SnPb	482, 504, 697, 744, 891, 913, 997, 1073, 1151, 1178, 1313, 1697, 1814, 2625, 3198, DNF, DNF, DNF, DNF, DNF
		SAC305_SAC305	315, 320, 338, 368, 407, 426, 441, 446, 447, 448, 458, 497, 499, 504, 506, 513, 536, 548, 555, 563, 571, 590, 624, 630, 647, 700, 702, 746, 765, 800, 800, 840, 943, 947, 1066, 1123, 1186, 1235, 1278, 1471, 1488, 1521, 1585, 1591, 1885, 3051, DNF
		SN100C_SAC305	304, 334, 335, 364, 373, 391, 408, 430, 439, 440, 474, 479, 486, 490, 498, 540, 559, 590, 594, 624, 624, 625, 627, 671, 688, 691, 748, 751, 764, 850, 887, 965, 970, 1102, 1146, 1170, 1216, 1241, 1290, 1404, 1598, 1795, 2471, 2491, DNF, DNF, DNF, DNF
		SnPb_SAC305	341, 348, 355, 368, 373, 390, 390, 391, 392, 395, 399, 405, 415, 419, 444, 444, 457, 460, 490, 490, 490, 494, 504, 510, 559, 562, 563, 564, 596, 624, 624, 648, 655, 664, 672, 687, 691, 698, 735, 772, 789, 800, 802, 810, 813, 826, 844, 848, 884, 917, 933, 976, 1110, 1173, 1194, 1221, 1244, 1322, 1333, 1345, 1383, 1422, 1425, 1429, 1663, 1723, 1738, 1785, 2064, 3313, 4043, DNF, DNF, DNF, DNF
	ENIG	*SAC305_SnPb*	*501, 674, 717, 1291, 3172*
		SAC305_SAC305	*426, 450, 624, 687, 1401*
		SnPb_SAC305	*390, 391, 407, 430, 440, 497, 559, 985, 1204, 1581*

Part Style	Board Finish	Solder_ Component Finish	Failure Data
QFN-20	ImAg	SAC305_Matte Sn	1480, 3205, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF
		SN100C_Matte Sn	2671, 3337, 3911, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF
		SnPb_Matte Sn	DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF
		SAC305_SnPb	1916, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF
	ENIG	*SAC305_Matte Sn*	*DNF, DNF, DNF, DNF, DNF*
		SnPb_Matte Sn	*DNF, DNF, DNF, DNF, DNF*

Part Style	Board Finish	Solder_ Component Finish	Failure Data
TQFP-144	**ImAg**	SAC305_Matte Sn	1043, 1056, 1189, 1271, 1300, 1311, 1325, 1328, 1334, 1344, 1356, 1359, 1367, 1386, 1388, 1413, 1413, 1427, 1430, 1441, 1466, 1499, 1500, 1509, 1510, 1511, 1534, 1566, 1581, 1593, 1648, 1668, 1762, 1791, 1837, 1874, 1942, 1945, 2045, 2069, 2086, 2126, 2202, 2360, 2425, 2436, 2644
		SN100C_Matte Sn	826, 1179, 1213, 1255, 1291, 1304, 1309, 1322, 1330, 1348, 1367, 1415, 1432, 1436, 1485, 1491, 1568, 1573, 1573, 1577, 1593, 1617, 1651, 1664, 1677, 1677, 1681, 1707, 1711, 1711, 1712, 1729, 1735, 1801, 1808, 1811, 1874, 1874, 1900, 1955, 1963, 1969, 1985, 2024, 2045, 2199, 2416
		SnPb_Matte Sn	1322, 2060, 2261, 2268, 2324, 2371, 2580, 2660, 2666, 2667, 2700, 2704, 2711, 2839, 2868, 2910, 2912, 2926, 2928, 3048, 3052, 3137, 3144, 3175, 3289, 3291, 3307, 3665
		SAC305_SnPb Dip	2291, 2550, 2662, 2669, 2768, 2967, 3167, 3173, 3174, 3241, 3286, 3317, 3331, 3442, 3460, 3541, 3544, 3579, 3612, 3685, 3704, DNF, DNF, DNF
		SN100C_SnPb Dip	1676, 1846, 1875, 1877, 1885, 1984, 1984, 2045, 2050, 2270, 2293, 2344, 2447, 2608, 2609, 2659, 2664, 2667, 2673, 2763, 2817, 2971, 3173, 3258, 3531
		SnPb_SnPb Dip	1985, 2098, 2162, 2222, 2379, 2422, 2447, 2480, 2488, 2502, 2515, 2547, 2574, 2587, 2597, 2630, 2648, 2666, 2667, 2675, 2686, 2690, 2716, 2739, 2747, 2753, 2763, 2778, 2786, 2849, 2866, 2890, 2906, 2912, 2930, 3034, 3095, 3127, 3141, 3182, 3389, 3516, 3755, DNF
		SAC305_NiPdAu	351, 2109, 2295, 2696, 2702, 2763, 2850, 3029, 3054, 3073, 3090, 3113, 3118, 3119, 3283, 3478, 3478, 3496, 3637, 3851, 3860, 3932, DNF, DNF, DNF
		SnPb_NiPdAu	1169, 1321, 1429, 1711, 1744, 1874, 1920, 1928, 1985, 1992, 2023, 2045, 2045, 2120, 2182, 2206, 2379, 2401, 2419, 2452, 2455, 2567, 2924, 3167, DNF
	ENIG	*SAC305_Matte Sn*	*1981, 2369, 2895, 3643, 3643*
		SAC305_SnPb Dip	*3827, 3850, DNF, DNF*
		SnPb_SnPb Dip	*2226, 2261, 2442, 2604, 2660*
		SnPb_NiPdAu	*1307, 1565, 1686, 2301, 2431*

Part Style	Board Finish	Solder_ Component Finish	Failure Data
BGA-225	**ImAg**	SAC305_SnPb	166, 209, 624, 801, 1070, 1415, 1568, 1590, 1608, 1622, 1628, 1644, 1647, 1656, 1668, 1689, 1690, 1695, 1698, 1702, 1713, 1718, 1724, 1756, 1759, 1770, 1802, 1806, 1815, 1822, 1831, 1836, 1864, 1920, 1926, 1932, 1936, 1967, 1986, 2033, 2088, 2156, 2499, 3167, DNF
		SN100C_SnPb	216, 251, 278, 342, 390, 391, 411, 564, 709, 739, 815, 1064, 1191, 1261, 1466, 1735, 1761, 1839, 1880, 1886, 2004, 2285, 2367, 2447, 2543
		SnPb_SnPb	2041, 2143, 2162, 2184, 2197, 2201, 2207, 2274, 2304, 2308, 2330, 2353, 2411, 2431, 2451, 2515, 2532, 2556, 2567, 2623, 2679, 2744, 2787, 2823, 2925
		SAC305_SAC405	2509, 2547, 2664, 2679, 2681, 2717, 2742, 2763, 2765, 2799, 2810, 2848, 2881, 2893, 2893, 2900, 2925, 2928, 2942, 2970, 2976, 2984, 2985, 3021, 3023, 3059, 3063, 3065, 3088, 3117, 3143, 3167, 3173, 3178, 3185, 3224, 3246, 3302, 3313, 3322, 3328, 3337, 3396, 3397, 3400, 3457, 3478, 3503, 3512, 3528, 3547, 3586, 3627, 3638, 3667, 3674, 3708, 3717, 3754, 3911, DNF, DNF, DNF, DNF, DNF
		SN100C_SAC405	308, 2079, 2357, 2771, 2772, 2789, 2800, 2905, 3019, 3072, 3134, 3159, 3181, 3291, 3305, 3326, 3388, 3407, 3421, 3441, 3458, 3482, 3540, 3567, 3589, 3590, 3597, 3602, 3602, 3611, 3623, 3643, 3671, 3718, 3719, 3734, 3739, 3741, 3770, 3777, 3778, 3782, 3812, 3812, 3846, 3849, 3954, 4012, 4012, 4017, 4043, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF
		SnPb_SAC405	443, 605, 624, 659, 1062, 1309, 1386, 1512, 1515, 1566, 1617, 2238, 2355, 2454, 2543, 2659, 2663, 2765, 3347, 3629, 3678, 3769, 3778, 3785, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF
	ENIG	*SAC305_SnPb*	*111, 1117, 1383, DNF, DNF*
		SAC305_SAC405	*2819, 3697, 3769, DNF, DNF*
		SnPb_SAC405	*3676, DNF, DNF, DNF*

Part Style	Board Finish	Solder_ Component Finish	Failure Data
CSP-100	**ImAg**	SAC305_SnPb	355, 2516, 2577, 2685, 2762, 2768, 2888, 2915, 2927, 2944, 3011, 3017, 3099, 3106, 3159, 3227, 3231, 3238, 3238, 3242, 3243, 3272, 3293, 3294, 3298, 3302, 3317, 3320, 3335, 3348, 3402, 3413, 3417, 3440, 3471, 3498, 3617, 3854, DNF, DNF, .
		SN100C_SnPb	851, 2577, 2715, 2733, 2735, 2778, 2784, 2802, 2840, 2855, 2890, 2895, 2932, 2991, 2995, 3034, 3078, 3129, 3199, 3217, 3270, 3289, 3442, DNF
		SnPb_SnPb	2248, 2447, 2451, 2481, 2557, 2573, 2600, 2636, 2690, 2704, 2728, 2742, 2749, 2801, 2837, 2841, 2843, 2858, 2941, 3043, 3109, 3114, 3234, 3253, 3336
		SAC305_SAC105	626, 2521, 2897, 3345, 3390, 3420, 3450, 3485, 3494, 3503, 3512, 3543, 3561, 3603, 3607, 3639, 3663, 3665, 3744, 3753, 3776, 3799, 3801, 3809, 3816, 3820, 3900, 3908, 3932, 3933, 3942, 3994, 4005, 4009, 4012, 4016, 4043, 4045, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF
		SN100C_SAC105	2769, 2799, 3012, 3173, 3322, 3351, 3411, 3451, 3494, 3495, 3507, 3513, 3571, 3610, 3685, 3761, 3783, 3800, 3805, 3816, 3850, 3901, 3908, DNF, DNF
		SnPb_SAC105	287, 335, 2708, 2906, 3145, 3531, 3683, 3721, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF
	ENIG	*SAC305_SnPb*	*2123, 2214, 2564, 2825, 3052*
		SAC305_SAC105	*3661, DNF, DNF, DNF, DNF*
		SnPb_SAC105	*280, 3485, DNF, DNF*

Part Style	Board Finish	Solder_ Component Finish	Failure Data
TSOP-50	**ImAg**	SAC305_SnPb	884, 934, 956, 1066, 1108, 1119, 1164, 1192, 1217, 1258, 1275, 1291, 1322, 1322, 1374, 1387, 1393, 1393, 1412, 1417, 1438, 1445, 1483, 1506, 1508, 1516, 1678, 1720, 1731, 1787, 1815, 1909, 1916, DNF
		SN100C_SnPb	863, 866, 894, 914, 1058, 1069, 1089, 1189, 1189, 1214, 1249, 1253, 1325, 1332, 1405, 1412, 1412, 1471, 1476, 1506, 1533, 1566, 1614, 1874, 1984
		SnPb_SnPb	1060, 1095, 1217, 1247, 1252, 1296, 1349, 1391, 1418, 1423, 1425, 1454, 1525, 1594, 1606, 1630, 1680, 1759, DNF
		SAC305_Sn	828, 854, 994, 1125, 1371, 1562, 1604
		SN100C_Sn	755, 930, 934, 985, 1012, 1180, 1258, 1296
		SnPb_Sn	1141, 1154, 1159, 1219, 1309, 1312, 1322, 1337, 1349, 1364, 1393, 1461, 1506, 1550, 1657
		SAC305_SnBi	789, 811, 860, 874, 888, 922, 933, 948, 952, 965, 988, 1006, 1008, 1077, 1087, 1098, 1099, 1123, 1127, 1147, 1154, 1168, 1185, 1195, 1199, 1221, 1227, 1244, 1248, 1265, 1269, 1279, 1302, 1334, 1352, 1380, 1409, 1422, 1486, 1497, 1525, 1532, 1549, 1585, 1594, 1597, 1701
		SN100C_SnBi	790, 831, 851, 887, 901, 904, 915, 933, 937, 941, 943, 1056, 1077, 1088, 1119, 1135, 1139, 1150, 1151, 1153, 1185, 1189, 1211, 1218, 1229, 1247, 1261, 1329, 1333, 1413, 1519, 1522
		SnPb_SnBi	343, 1018, 1057, 1144, 1195, 1218, 1251, 1269, 1272, 1274, 1280, 1290, 1315, 1322, 1341, 1349, 1353, 1354, 1358, 1368, 1370, 1386, 1386, 1404, 1418, 1424, 1446, 1455, 1458, 1460, 1487, 1487, 1502, 1520, 1577, 1593, 1657, 1678
	ENIG	*SAC305_SnPb*	*281, 1491, 1667, 1877, 2110*
		SnPb_Sn	*1097, 1154, 1186*
		SAC305_SnBi	*1141, 1320, 1434, 1508, 1529*

Part Style	Board Finish	Solder_ Component Finish	Failure Data
PDIP-20	**ImAg**	SAC305_NiPdAu	1322, DNF, DNF, DNF, DNF
		SN100C_NiPdAu	124, 238, 280, 335, 348, 691, 1037, 1136, 1298, 1533, 1565, 2003, 2325, 2446, 2654, 2884, 3544, 4012, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF
		SnPb_NiPdAu	DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF
		SAC305_Sn	1593, DNF, DNF, DNF, DNF
		SN100C_Sn	111, 143, 203, 209, 277, 277, 333, 333, 391, 395, 408, 504, 513, 590, 628, 634, 646, 654, 660, 667, 703, 766, 828, 834, 835, 855, 925, 945, 953, 960, 975, 1024, 1039, 1145, 1448, 1525, 1818, 1976, 2314, 2454, 2771, 2944, 2956, 3202, 3423, 3597, 3812, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF
		SnPb_Sn	682, 935, 1010, 1031, 1095, 1127, 1830, 2372, 2725, 2858, 2911, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF
	ENIG	*SN100C_NiPdAu*	*2309, 3603, 3620, DNF, DNF, DNF, DNF*
		SnPb_NiPdAu	*DNF, DNF, DNF*
		SN100C_Sn	*2044*
		SnPb_Sn	*DNF, DNF, DNF*

Appendix I Failure Data - Reworked Components

Part Style	Board Finish	Solder_ Component Finish: rework	Failure Data
CLCC-20	ImAg	SAC305_SAC305: 1 rework with SnPb	319, 415, 508, 591, 699, 749, 936, 945, 952, 2068, DNF, DNF
		SN100C_SAC305: 1 rework with SnPb	545, 796, 801, 805, 914, 972, 1021, 1377, 1741
		SAC305_SAC305: 1 rework with SAC305	735
		SAC305_SAC305: 2 rework with SnPb	473, 547, 695, 715, 744, 900, 1009, 2019, 2263
		SN100C_SAC305: 2 rework with SnPb	600, 706, 769, 806, 821, 1192, 1256, 2615
QFN-20	ImAg	SAC305_Matte Sn: 1 rework with SnPb	DNF, DNF, DNF, DNF, DNF, DNF, DNF
		SN100C_Matte Sn: 1 rework with SnPb	277, 1416, DNF, DNF, DNF, DNF
		SAC305_Matte Sn: 2 rework with SnPb	DNF, DNF, DNF, DNF, DNF, DNF
		SN100C_Matte Sn: 2 rework with SnPb	DNF, DNF, DNF, DNF, DNF, DNF, DNF
		SAC305_Matte Sn: StencilQuik rework with SnPb	3660, DNF, DNF, DNF, DNF, DNF, DNF
		SN100C_Matte Sn: StencilQuik rework with SnPb	3547, DNF, DNF, DNF, DNF, DNF, DNF
TQFP-144	ImAg	SAC305_Matte Sn: 1 rework with SnPb	1556, 2149, 2379, 2452, 2597, 2911, 2969, 3305, 3775
		SN100C_Matte Sn: 1 rework with SnPb	1493, 1589, 2032, 2137, 2267, 2281, 2350, 3710, DNF
		SAC305_Matte Sn: 2 rework with SnPb	2156, 2160, 2198, 2348, 2447, 2536, 2882, 3546, DNF
		SN100C_Matte Sn: 2 rework with SnPb	1758, 1914, 2069, 2356, 2408, 2460, 3166, DNF, DNF

Part Style	**Board Finish**	**Solder_ Component Finish: rework**	**Failure Data**
BGA-225	**ImAg**	SnPb_SnPb: 1 rework with SnPb	813, 931, 1058, 1170, 1446, 1460, 2117, 2137, 2478, 2994, 3284, 3489, 3590, DNF, DNF
		SAC305_SAC405: 1 rework with SnPb	2138, 2673, 3786, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF
		SnPb_SnPb: 1 rework with Flux Only	2144, 2172, 2253, 2349, 2380, 2428, 2455, 2627, 2689, 2700
		SAC305_SAC405: 1 rework with Flux Only	983, 2662, 2925, 3182, 3399, 3417, 3609, 3648, 3667, 3757, 3803, 3826, 3827, 3924, DNF
		SnPb_SAC405: 1 rework with Flux Only	1907, 2210, 2483, 2489, 3032
	ENIG	*SnPb_SnPb: 1 rework with SnPb*	*DNF, DNF, DNF*
		SnPb_SnPb: 1 rework with Flux Only	*1760, 2122*
		SnPb_SAC405: 1 rework with Flux Only	*1794*
CSP-100	**ImAg**	SnPb_SnPb: 1 rework with SnPb	DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF
		SAC305_SAC105: 1 rework with SnPb	DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF
		SAC305_SAC105: 1 rework with SAC305	3795
		SnPb_SnPb: 1 rework with Flux Only	2550, 2578, 2688, 2773, 2782, 2786, 2874, 2994, 3012, 3033, 3063, 3121, 3192, 3291, 3430
		SAC305_SAC105: 1 rework with Flux Only	3458, 3848, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF
		SAC305_SAC105: 2 rework with Flux Only	2299, 2483, 3167
	ENIG	*SnPb_SnPb: 1 rework with SnPb*	*3488, DNF, DNF*
		SnPb_SnPb: 1 rework with Flux Only	*1525, 1874, 2212*

Part Style	Board Finish	Solder_ Component Finish: rework	Failure Data
TSOP-50	**ImAg**	SnPb_SnPb: 1 rework with SnPb	272, 1120, 1128, 1222, 1306, 1317, 1324, 1425, 1443, 1513, 1522, 1588, 1615, 1660, 1664, 1691, 1774, 1818, 1840, 1993
		SAC305_Sn: 1 rework with SnPb	824, 1010, 1075, 1178, 1322, 1333, 1432, 1513, 1521, 1525, 1680, 1878, 1889, 2010, 2021, 2096
		SN100C_Sn: 1 rework with SnPb	1058, 1148, 1341, 1545, 1550, 1562
		SAC305_SnBi: 1 rework with SnPb	801, 934, 1028, 1160, 1531, 1561
		SN100C_SnBi: 1 rework with SnPb	801, 968, 1039, 1328, 1588, 1778
		SAC305_SnPb: 1 rework with SAC305	765, 1010, 1322, 1687
		SAC305_SnBi: 1 rework with SAC305	879, 1029, 1063, 1155, 1156, 1189, 1207, 1290, 1412, 1498
		SAC305_Sn: 2 rework with SnPb	963, 1093, 1130, 1173, 1365, 1456, 1525
		SN100C_Sn: 2 rework with SnPb	963, 1145, 1322, 1334, 1455, 1569
		SAC305_SnBi: 2 rework with SnPb	933, 1438, 1449, 1501, 1572, 1810, 1856
		SN100C_SnBi: 2 rework with SnPb	326, 1142, 1189, 1285, 1369, 1603, 1654
	ENIG	*SnPb_SnPb: 1 rework with SnPb*	*336, 1517, 1578, 1941*
PDIP-20	**ImAg**	SnPb_SnPb: 1 rework with SnPb	928, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF
		SN100C_NiPdAu: 1 rework with SnPb	34, 76, 166, 277, 307, 544, 643, 1580, DNF, DNF
		SN100C_Sn: 1 rework with SnPb	209, 213, 269, 282, 456, 501, 666, 684, 950, 1045, 1222, 4043, DNF
		SN100C_Sn: 1 rework with SN100C	2304, 2657, 2840, DNF, DNF, DNF, DNF, DNF, DNF, DNF
		SN100C_NiPdAu: 2 rework with SnPb	88, 118, 167, 212, 340, 645, 783
		SN100C_Sn: 2 rework with SnPb	111, 111, 373, 692, 962
	ENIG	*SnPb_SnPb: 1 rework with SnPb*	*DNF, DNF*